EFFECT OF SYNTHETIC FIBERS AND A RHEOLOGY MODIFIER ON SETTLEMENT CRACKING OF CONCRETE

By
Osama Al-Qassag
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A Report on Research Sponsored by

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Structural Engineering and Engineering Materials
SM Report No. 116
December 2015

THE UNIVERSITY OF KANSAS CENTER FOR RESEARCH, INC.
2385 Irving Hill Road, Lawrence, Kansas 66045-7563

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ABSTRACT

Three series of concrete mixtures, consisting of 133 batches, were tested. The first series consisted of 27 control mixtures with a 24.3 percent cement paste content by volume and a water-to-cement ratio of 0.5. The second series consisted of 18 control mixtures with a 27 percent cement paste content by volume and a water-to-cement ratio of 0.45. The third series consisted of 88 mixtures with a 27 percent cement paste content and a water-to-cement ratio of 0.45. Fourteen batches in the third series served as controls; the remaining 74 mixtures were used to evaluate the effectiveness of crack reduction technologies on settlement cracking performance; fifty-seven mixtures contained from 1.5 lb/yd^3 (0.89 kg/m^3) to 7.5 lb/yd^3 (4.45 kg/m^3) of one of four different synthetic fibers, and 17 mixtures contained a rheology modifier in the form of a dry viscosity modifying admixture (dosed at 0.05% of mixture material dry weight).

The results showed that settlement cracking increased as the slump of the mixture increased. The addition of fibers or the viscosity modifying admixture reduced settlement cracking compared to the mixtures without the additions. For a given slump, mixtures containing fibers exhibited less settlement cracking than the mixtures containing the viscosity modifying admixture. For a given slump, concrete containing the viscosity modifying admixture was more workable when shear force is applied compared to concrete containing fibers. With one exception, differences in settlement cracking as a function of fiber type were not statistically significant.

Keywords: concrete, crack reduction technologies, settlement cracking, slump, rheology, synthetic fibers, viscosity modifying admixture.

ACKNOWLEDGEMENTS

This report is based on research performed by Osama Al-Qassag in partial fulfillment of the requirements for the MSCE degree from the University of Kansas. Support was provided by the ACI Foundation and sponsoring organizations: ABC Polymers, the ACI Foundation's Strategic Development Council (SDC), Active Minerals International, the American Society of Concrete Contractors, Baker Concrete Construction, BASF Corporation, FORTA Corporation, the Expanded Shale, Clay and Slate Institute, the Euclid Chemical Company, the University of Kansas Transportation Research Institute, PNA Construction Technologies, Inc., Premier Construction Products, Sika Corporation, Structural Group, Inc., and W. R. Grace and Company.

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Chapter 1 INTRODUCTION

1.1 General

Cracking of reinforced concrete bridge decks represents a significant problem in terms of bridge integrity and maintenance costs. Such cracks significantly reduce the service life of bridge decks by accelerating freeze-thaw damage and exposing the steel reinforcement to corrosive salts. These cracks provide paths for water, oxygen, and deicing salts to penetrate through the bridge decks and reach reinforcing steel; these paths can extend partially or entirely through the bridge deck. After water penetrates into bridge decks, freeze-thaw damage occurs because of the expansion of frozen water in the cracks. Moreover, as deicing salts are added for the purpose of ice removal from the decks, corrosion of reinforcement is significantly increased in the presence of cracks. Sodium chloride and calcium chloride are the most common types of deicing salts and have been used for many decades for this purpose. When the concentration of chlorides from these chemicals reaches the critical chloride corrosion threshold, corrosion starts and expansive corrosion products cause delamination and spalling in the bridge deck. Chlorides can also degrade the epoxy coating protecting reinforcement against corrosion (Darwin et al. 2011). The National Bridge Inventory (NBI) states that bridge deck deterioration caused by concrete distress and reinforcement corrosion is the main reason for structural deficiency of bridges (Russell 2004).

Concrete has a high compressive strength but a low tensile strength; typically, concrete tensile strength is equal to one-tenth of its compressive strength. When tensile stresses in bridge decks exceed the concrete tensile strength, cracks start to develop. Several factors can lead to the development of tensile stresses in concrete in bridge decks, such as the settlement of plastic concrete over reinforcement, plastic shrinkage, drying shrinkage, thermal shrinkage, and traffic loading. These factors are mainly influenced by concrete properties, environmental conditions, construction methods, and structural design of bridges.

In 2005, the annual direct costs of bridge deck corrosion was estimated at $8.3 billion (Yunovich et al. 2005). Therefore, eliminating or reducing bridge deck cracking is extremely important. Since the 1960s, many transportation agencies have been involved in research programs in order to produce a higher performance and more durable concrete. Prior research at the University of Kansas has identified typical causes and proposed solutions for different types of cracks such as plastic shrinkage cracking, thermal shrinkage cracking, drying shrinkage cracking, and flexural cracking (Lindquist et al. 2008). The goal of this research has been to eliminate or reduce cracks by improving the materials and construction procedures used for bridge decks. New materials are being applied to improve the internal curing potential using lightweight aggregates. Mineral admixtures and shrinkage reducing admixtures (SRAs) are being applied to improve concrete durability and reduce cracking (Pendergrass and Darwin 2014). This study focuses on the implementation of new technologies to reduce settlement cracking in concrete. The first part of this study is to develop a procedure that yields consistent results in tests for settlement cracking. The second part is to evaluate the effect of different types of synthetic fibers and a rheology modifying admixture on the settlement cracking performance.

1.2 Significance of Bridge Deck Cracking

Many local transportation agencies in the United States have acknowledged that cracking of bridge decks creates serious problems that affect its durability. A survey of transportation agencies was performed to better understand and evaluate the effect of transverse cracking on bridge decks (Krauss and Rogalla 1996). Among the 52 agencies that responded, 62% acknowledged early age transverse cracking as a serious problem that affects the durability of bridge decks, whereas the rest acknowledged the existence of the transverse cracks, but did not consider them as causing problems with durability (Krauss and Rogalla 1996). The following sections illustrate the influence of cracking on bridge becks.

1.2.1 Influence on Corrosion of Reinforcing Steel

To better understand the influence of cracks on the corrosion of reinforcing steel, we must identify the value of the chloride-induced corrosion threshold. A conservative value of 1.0 lb/yd^3 (0.6 kg/m^3) is widely accepted as a corrosion threshold for uncoated steel reinforcement. Research by Lindquist et al. (2005) has shown that the average chloride concentration at a depth equal to 3.0 in. (76.2 mm) in cracked bridge decks can reach and even exceed the value of the corrosion threshold in as little as nine months. On the other hand, it was found that chloride concentrations in uncracked decks remained below the corrosion threshold for at least 96 months (8 years), with about 50% of bridge decks having chloride concentrations remaining below the threshold up to 254 months (21.2 years) after construction. Figures 1.1 and 1.2 illustrate the relationship between chloride concentration and bridge deck age. These figures show that the chloride concentration in cracked decks increases at a significantly higher rate than in uncracked decks (Lindquist et al. 2005). If conventional reinforcement is used, corrosion products occupy a larger volume than the original volume of the steel, leading to delamination of concrete in a bridge deck.

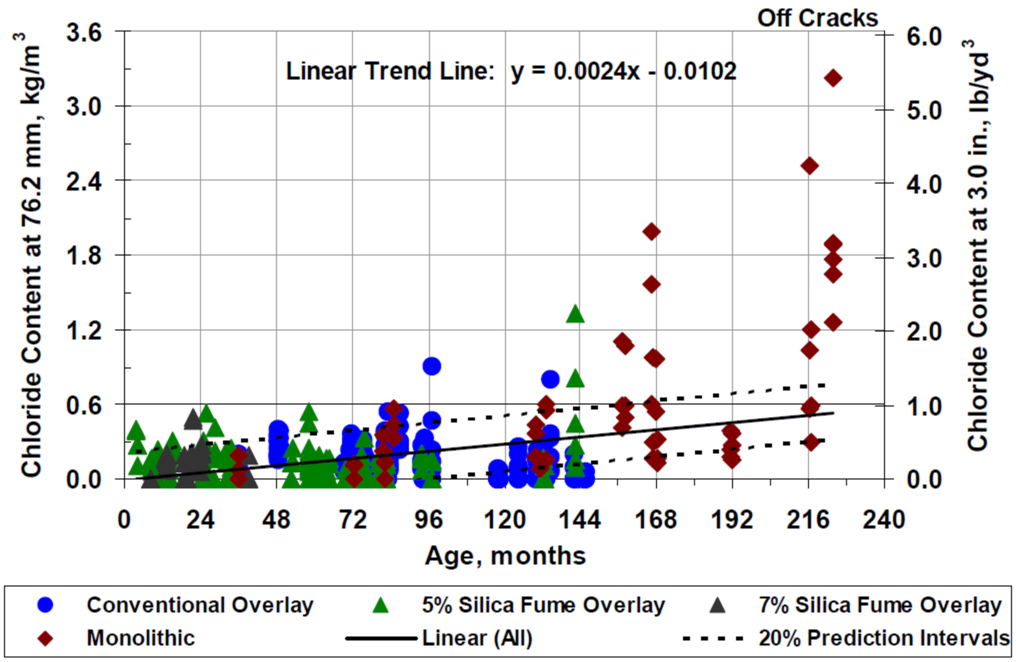


Figure 1.1: Chloride content at a depth of 76.2 mm (3 in.) measured away from cracks versus age of bridge deck, with 20% upper and lower bounds (Lindquist et al. 2005).

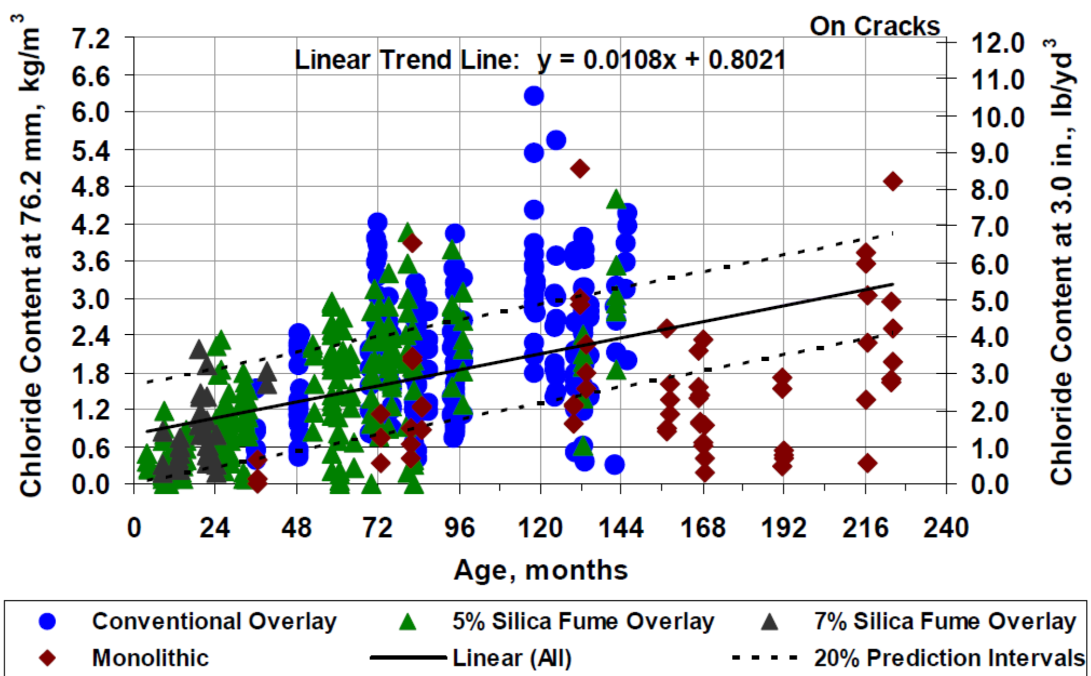


Figure 1.2: Chloride content at a depth of 76.2 mm (3 in.) measured on cracks versus age of bridge deck, with 20% upper and lower bounds (Lindquist et al. 2005).

Even though epoxy-coated reinforcement (ECR) is widely used in the United States as a means to protect the reinforcing steel from corrosion, a study by Fanous and Wu (2005) showed that corrosion occurs in ECR in cracked concrete (the nature of the cracks was not described), while ECR was found to be uncorroded at uncracked sections; the chloride concentrations at bar levels was higher than the corrosion threshold in both cracked and uncracked concrete. These studies clearly proved that eliminating or reducing cracks in bridge decks can reduce corrosion of reinforcing steel.

1.2.2 Influence on Bridge Deck Concrete

Cracks accelerate freeze-thaw damage in concrete. When water penetrates bridge deck cracks, it can fill the cracks and expand upon freezing, resulting in damage to the deck concrete.

1.2.3 Influence on Bridge Maintenance Costs

Bridge deck maintenance costs for cracking-related problems are high in terms of financial commitments and delay of traffic. In 1978, approximately one-third of all bridge decks in the United States had deteriorated because of the corrosion of reinforcing steel with a $6.3 billion cost for repair. In 2005, the average annual direct cost of bridge deck corrosion was $8.3 billion (Yunovich et al. 2005), with related costs of traffic delay estimated as 10 times that cost (Thompson et al. 2005). Therefore, attention has been increased over the past decades to reduce or eliminate cracks in bridge decks in order to control its deterioration and minimize the costs of maintenance.

1.3 Types of Cracks

Cracks can be classified based on either the causes of cracking or their orientation. Several factors can lead to the development of different types of cracks in bridge decks. However, the different types of cracks are not independent of each other. These crack types and their causes are discussed in the following sections.

1.3.1 Categorizing Cracks Based on the Causes of Cracking

Cracks can be categorized into those occurring in plastic concrete cracking and those occurring in hardened concrete. Cracks in plastic concrete include settlement/subsidence and plastic shrinkage cracks, while cracks in hardened concrete include drying shrinkage, thermal shrinkage, and flexural cracks.

1.3.1.1 Settlement/Subsidence Cracking

After placement and consolidation, plastic concrete continues to settle around fixed objects such as reinforcing bars. This settlement can result in the formation of cracks directly above and parallel to the reinforcing bars in bridge decks. Even though cracks may not be visible immediately after the concrete has hardened, weakened planes can develop above the reinforcing bars that can increase the probability of other types of cracking over time (Babaei and Purvis 1995). Inadequate consolidation during the construction of bridge decks can increase the probability of settlement cracking. The key factors affecting settlement cracking include concrete slump, concrete cover, and reinforcing bar size. Settlement cracking can be reduced by increasing concrete cover and reducing concrete slump and reinforcing bar size (Dakhil et al. 1975). The current study targets reducing settlement cracking in bridge decks. Section 1.6 describes settlement cracking and suggests new technologies to minimize it, in greater detail.

1.3.1.2 Plastic Shrinkage Cracking

Plastic shrinkage cracking occurs when the rate of evaporation of plastic concrete surface exceeds the rate of bleed water reaching the surface. Tensile stresses are developed because of the differential shrinkage, as the upper layer of concrete shrinks but is restrained by the lower layer.

Plastic concrete at early ages has no significant capacity to resist tensile stress. Therefore, as water evaporates from the surface, cracks start to develop because of the tensile stresses induced in capillary pores. To reduce plastic shrinkage cracking, the rate of evaporation needs to be reduced or the bleed water needs to be increased. The rate of evaporation decreases as concrete and air temperature and, wind speed decrease, and relative humidity increases. Figure 1.3 shows a nomograph that relates the rate of evaporation to relative humidity, air temperature, concrete temperature, and wind speed (ACI Committee 308).

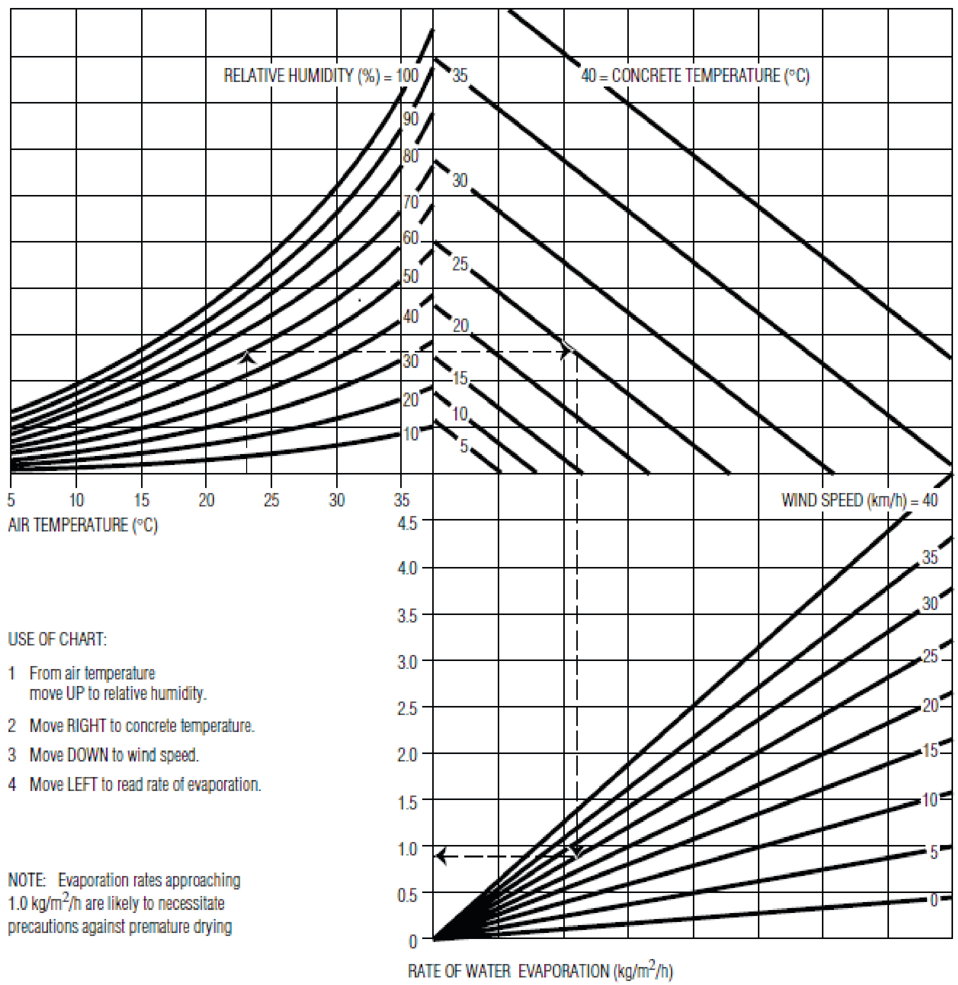


Figure 1.3: Effect of air temperature, relative humidity, concrete temperature, and wind speed on the rate of evaporation of surface moisture from concrete (ACI Committee 308).

When the rate of evaporation is below 0.2 $lb/ft^2/hr$ (1 $kg/m^2/hr$), the probability of plastic shrinkage cracking is reduced. Furthermore, the rate of water bleeding is directly affected by concrete material properties. For instance, the bleeding rate is decreased by using mineral admixtures and finely-ground cement, adding air-entraining agents, decreasing water-cement and water-cementitious material ratios (w/c and w/cm), and increasing the rate of cement hydration (Mindess et al. 2003). Plastic shrinkage cracking can be reduced using an evaporation retarder, windbreaks, curing compound, and fogging equipment to maintain a high relative humidity above the concrete area. Admixtures that increase water bleeding, polyethylene sheets, and other wet curing materials, such as burlap, can reduce plastic shrinkage cracking.

1.3.1.3 Drying Shrinkage Cracking

Drying shrinkage occurs in hardened concrete because of water loss from the capillary pores in cement paste (hardened calcium silicate hydrate [C-S-H] gel). Drying shrinkage cracks initiate as concrete shrinks and is restrained by reinforcing steel and attached structural members, such as bridge girders. Moreover, differential or non-uniform shrinkage throughout the deck thickness develops restraint and results in drying shrinkage cracking as shrinkage of the surface layer is restrained by the interior concrete (Bisschop and Van Mier 2000). The use of stay-in-place forms can aggravate the gradient in moisture content because the bottom surface of the deck does not lose moisture due to the presence of the forms. Drying shrinkage occurs over a long period. The greatest amount, however, occurs at an early age, with typically 80 percent of total drying shrinkage occurring during the first ninety days (Holt 2001). Early age cracking is irreversible and is always greater than any increase in volume with rewetting. Pickett (1956) and Helmuth and Turk (1956) concluded that irreversible shrinkage represents 60 percent of the change in volume on first drying. The large surface-to-volume ratio of a concrete bridge deck increases early age drying shrinkage because of the large surface exposure to ambient environmental.

The properties of concrete materials are the key factors in controlling drying shrinkage in bridge decks. The use of finely grounded cement increases drying shrinkage as it decreases capillary pore diameter and leads to greater capillary stress. Reducing the paste content reduces the shrinkable component in the concrete and, thus, reduces drying shrinkage. In addition, aggregate provides volume stability to the concrete because of its high stiffness; therefore, maximizing the aggregate content also reduces drying shrinkage. Research has shown that the use of saturated lightweight aggregate along with the use of ground granulated blast furnace slag (GGBFS), also known slag cement, reduces drying shrinkage (Reynolds et al. 2009). Creep can reduce the tensile stress developed because of shrinkage by reducing the concrete restraint and, therefore, can reduce drying shrinkage cracking.

1.3.1.4 Thermal Shrinkage Cracking

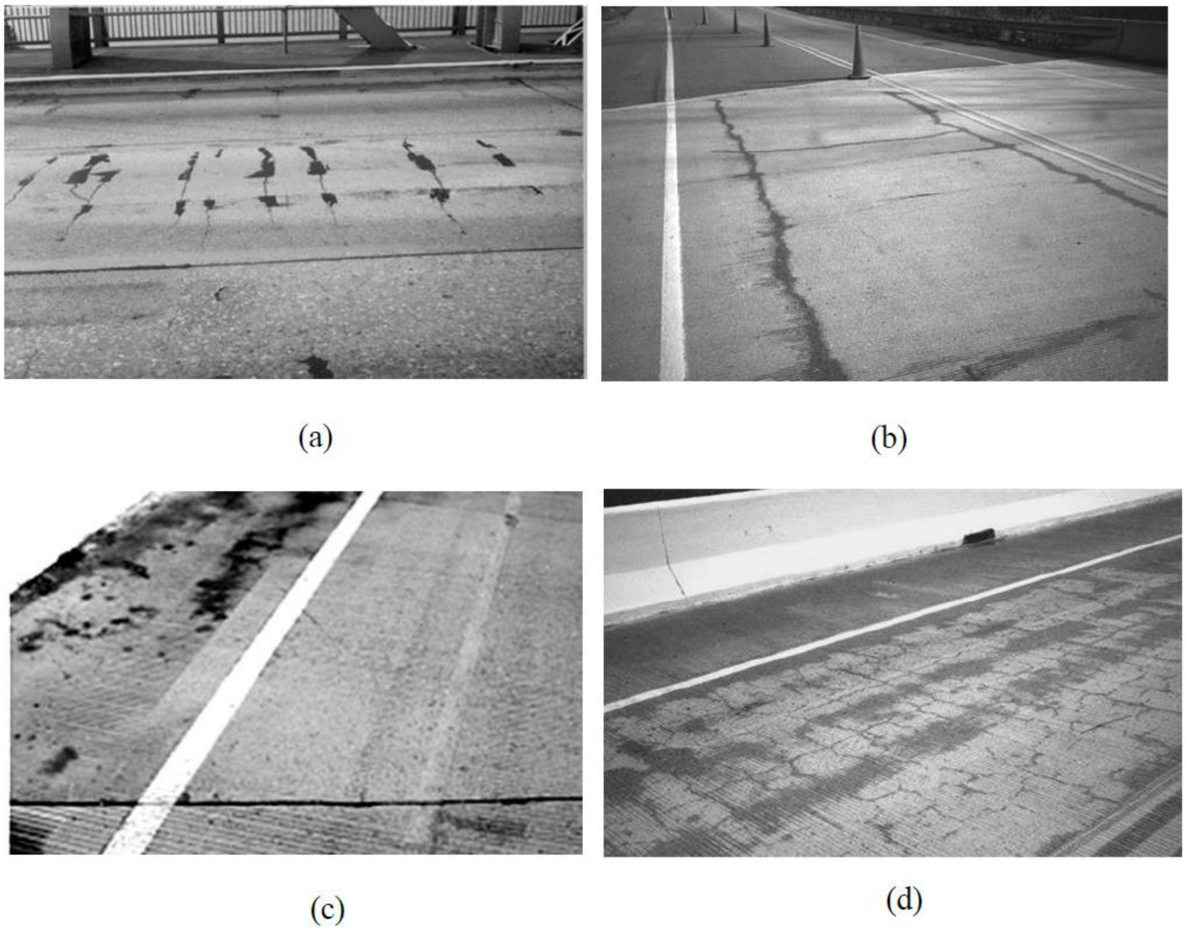
Thermal cracking results from concrete expansion and contraction due to thermally-induced strains. Plastic concrete expands because the hydration process generates heat. However, little or no stress develops in plastic concrete because of its low stiffness. As the hydration rate slows, concrete contracts as it cools. At this point, the stiffness of the concrete has increased. The contraction of the concrete is restrained by girders, reinforcement, shear studs, and abutments which can result in crack initiation (Babaei and Fouladgar 1997). The resulting thermally-induced stresses may make the deck more prone to cracking by other factors (Babaei and Purvis 1996). Thermal cracking can also result from the differences in thermal expansion coefficients between steel girders and concrete because the two materials do not expand at the same rate (Krauss and Rogalla 1996).

1.3.1.5 Flexural Cracking

Loads, including self-weight, superimposed dead load, construction loads, and traffic live loads can induce tensile stresses that initiate cracks in bridge decks, typically in the negative moment regions. However, flexural cracking is minimal compared to the previously discussed types of cracks and will be neglected (Krauss and Rogalla 1996).

1.3.2 Categorizing Cracks Based on Orientation

Cracks can be classified according to their orientation with respect to the longitudinal axis of a bridge. The orientation of cracks with respect to the reinforcing steel will determine the type of corrosion that occurs in the steel. When cracks are perpendicular to the reinforcing steel, the exposed area of steel is small, and localized corrosion occurs. However, when the crack orientation is parallel to the reinforcing steel, a larger area of steel is exposed and corrosion occurs over a large area of the bar. This type of cracking usually occurs because of the weakened planes above the reinforcing bars caused by settlement of plastic concrete. The Portland Cement Association (Durability 1970) has classified cracks in bridge decks into five categories according to orientation: transverse, longitudinal, pattern (map), diagonal, and random cracking. Figure 1.4 shows examples of transverse, longitudinal, diagonal, and map cracking.



(a) (b) (c) (d)

Figure 1.4: Different types of cracks according to their orientation (Durability 1970) : (a) transverse cracking, (b) longitudinal cracking, (c) diagonal cracking, (d) map cracking.

1.3.2.1 Transverse Cracking

Transverse cracking is the most common type of cracking found on bridge decks (Babaei and Purvis 1995, Krauss and Rogalla 1996, Le et al. 1998, Eppers et al. 1998, Lindquist et al. 2005). These type of cracks form perpendicular to the longitudinal axis of the bridge deck and extend above the reinforcing bars in both positive and negative moment regions (Babaei and Purvis 1995, Krauss and Rogalla 1996, Lindquist et al. 2005). The weakened planes caused by settlement cracking, drying shrinkage, and to a lesser extent, plastic shrinkage, are the cause of transverse cracking in bridge decks. Inadequate consolidation or cover thickness can also enhance the development of this type of cracking (McLeod et al. 2009). Transverse cracks can extend through the full thickness of bridge decks (Krauss and Rogalla 1996) and may occur at early ages before the bridge deck is open to service or at later ages (Durability 1970).

1.3.2.2 Longitudinal Cracking

Longitudinal cracks form parallel to the longitudinal axis of bridge decks. These cracks appear in both solid and hollow slab bridge decks as a result of settlement of the concrete, initiating above the longitudinal reinforcement in solid bridge deck and above the void tubs in hollow slab bridge decks. Short longitudinal cracks sometimes form at abutments, especially when the bridge deck is integrally cast with the abutment, because of the restraint provided by the abutments (Schmitt and Darwin 1995, Miller and Darwin 2000, Lindquist et al. 2005).

1.3.2.3 Diagonal Cracking

Diagonal cracks appear at the end of skewed bridge decks, near integral abutments, and over single column piers (Lindquist et al. 2005). Diagonal cracks are shallow, parallel to each other, and extend with an angle other than 90 degree with respect to the longitudinal axis of bridge. Flexural stresses induced by restraint at integral skewed abutments and drying shrinkage cause this type of cracking (Durability 1970).

1.3.2.4 Pattern (Map) Cracking

Pattern or map cracks consist of interlocking cracks of all different sizes found in all types of bridge decks. Generally, these cracks are shorter and shallower than other types of cracks and, therefore, have less effect on bridge deck durability and performance. Both plastic shrinkage and drying shrinkage cause pattern cracks (Durability 1970). Overfinishing the bridge deck can lead to greater access of cement past at the surface, resulting in more pattern cracking (Pendergrass and Darwin 2014).

1.4 Factors Affecting Bridge Deck Cracking

Many factors lead to bridge deck cracking. The key variables involve concrete material properties, construction methods, environmental conditions, and structural design (Pendergrass and Darwin 2014).

1.4.1 Concrete Material Properties

Concrete properties have the greatest effect on bridge deck cracking (Krauss and Rogalla 1996). Shrinkage of restrained concrete contributes to a significant amount of bridge deck cracking. The cement paste constituent of concrete has a significant effect on shrinkage–increasing water content or/and cementitious material content leads to a greater shrinkage (Pendergrass and Darwin 2014). Schmitt and Darwin (1999) studied the effect of paste content on 32 monolithic bridge decks and concluded that the optimum cement paste volume is 27 percent or less of the total concrete volume. Much greater cracking was observed for concretes with paste contents higher than 27 percent, as shown in Figure 1.5 (Schmitt and Darwin 1995).

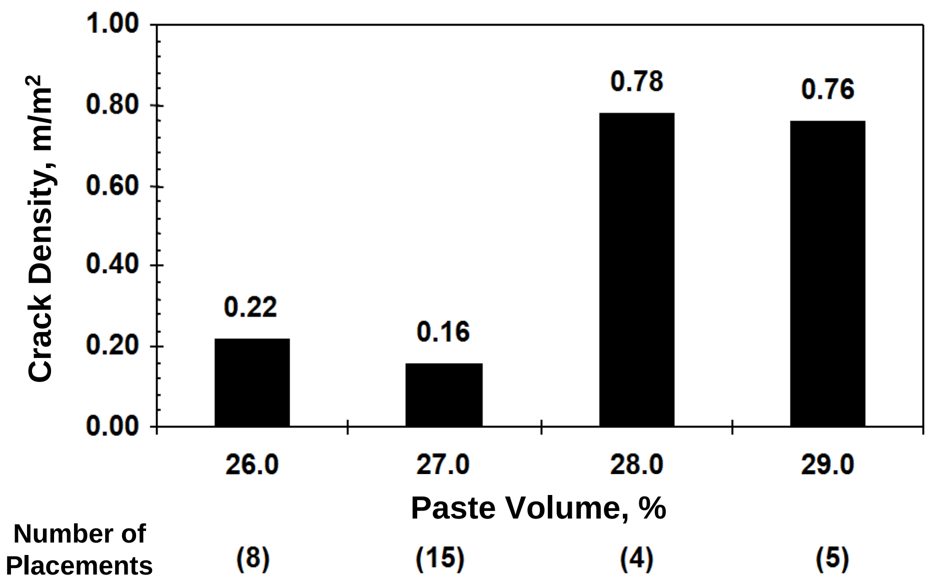


Figure 1.5: Effect of paste content on cracking density and optimum paste content that corresponds to minimum cracking density (Schmitt and Darwin 1995).

Deshpande et al. (2007) concluded that paste content had a much greater effect on shrinkage than either water-cement ratio, which had little impact at all for a given paste content, or cement type. Increasing the paste content of concrete from 20 to 30 percent and from 30 to 40 percent increased the free shrinkage by 150 με and 250 με, respectively.

Yuan et al. (2011) monitored time to cracking by conducting restrained ring tests. Increasing the paste content from 24 to 33 percent for concretes with a water-cement ratio of 0.45 led to a 9-days decrease in the time to cracking.

Several studies have linked a high cement content to high shrinkage and cracking (Krauss and Rogalla 1996, French et al. 1999, Brown et al. 2001, Lindquist et al. 2008). Shrinkage potential can be minimized by reducing cement content in concrete mixtures. Decreasing cement content decreases the heat of hydration and the resulting thermal stresses, resulting in improved cracking performance (Brown et al. 2001). Krauss and Rogalla (1996) conducted restrained and free shrinkage tests for several mixtures with varying cement content, water-cement ratio, water content, and paste content. In the free shrinkage tests, the researchers observed that the mixtures with highest cement content, 846 lb/yd^3 (502 kg/m^3), were the first to crack and mixtures with the lowest cement content, 470 lb/yd^3 (279 kg/m^3), were the last to crack. The restrained shrinkage tests showed a minor relationship between crack tendency and paste content.

French et al. (1999) studied the cracking performance of 21 concrete bridge decks and observed increased crack density with higher cement and paste contents.

Lindquist et al. (2008) used two series of tests to study the effect of paste content and water-cement ratio on the free shrinkage of concrete. The first series included different paste contents, achieved by varying the water content in mixtures with a constant cement content of 535 lb/yd^3 (317 kg/m^3). The paste content was reduced from 24.4 to 23.1 percent of the total concrete volume as the water-cement ratio was reduced from 0.45 to 0.41. A reduction in free shrinkage was observed with the lower paste content. The second series of tests included water-cement ratios of 0.36, 0.38, 0.40, and 0.42 with a constant paste content. No significant difference in shrinkage performance was observed between the mixtures after 365 days of drying, confirming that paste content is the primary contributor to concrete shrinkage.

Deshpande et al. (2007) and West et al. (2010) studied the effect of aggregate content on the performance of non-air-entrained concrete. A 139 με decrease in shrinkage was obtained after 180 days of drying as the aggregate content increased from 60 percent to 70 percent. After 365 drying days, a 183 με decrease in shrinkage was obtained for the same two mixtures. Hansen and Almudaiheem (1987) also studied the effect of aggregate content on shrinkage and observed a decrease of 18 percent in drying shrinkage as the aggregate content was increased from 65 percent to 70 percent.

1.4.2 Weather Conditions during Construction

Environmental conditions have a direct effect on the cracking performance of bridge decks. As the surface evaporation rate increases, drying and shrinkage of the deck surface increases. Moreover, air temperature, concrete temperature, and temperature differences between the girder and bridge deck all affect bridge deck cracking (Pendergrass and Darwin 2014).

French et al. (1999) studied the effect of air temperature on the day of deck placement on the cracking performance of bridge decks. That study included 18 bridges, 10 with prestressed girders and 8 with steel girders. Bridge decks with low cracking were cast on days in which the air temperature ranged between a low of 45° to 50° F (7° to 10° C) and high of 65° to 70° F (18° and 21° C) . Four of the prestressed girder bridges experienced high cracking–three of them were cast on days in which the air temperature was below 35° F (2° C) and the fourth was cast in a high air temperature around 90° F (32° C). French et al. (1999) stated that both a wide temperature range and a large decrease in air temperature on the placement date will contribute to higher cracking. In contrast, Lindquist et al. (2005) observed that cracking performance improves as the average and minimum air temperatures decrease on the placement date. The minimum daily air temperature for the day of placement for monolithic and overlay subdeck placements ranged from 19° F to 75° F (-7° to 24° C). The average air temperature during placement was 55° F (13° C) for monolithic decks and 68° F (20° C) for overlay subdecks. Neither French et al. (1999) nor Lindquist et al. (2005) considered the effect of concrete and ambient temperature differences during the placement, which might be the reason for the conflicting observations. Both Lindquist et al. and French et al. observed that the cracking increased as the range of air temperature increased on the placement date. Yuan et al. (2011) studied the effect of ambient temperature on the cracking performance of 40 monolithic bridge decks in Kansas and found a similar trend to that observed by Lindquist et al. (2005), confirming that cracking increases as the maximum air temperature increases on the placement date.

Thermal stresses and cracking caused by the restraint of concrete can result from the temperature differences between the deck concrete and girder. The higher concrete temperature and the lower girder temperature return to an intermediate ambient temperature over time. That adjustment in temperature results in tensile stresses in the deck because of the different coefficients of thermal expansion rate and the restraint provided by the girders (Pendergrass 2014).

Subramaniam and Agrawal (2009) examined tensile stresses in newly constructed bridge decks by monitoring the temperature and strain in both the concrete decks and the steel girders. Concrete temperature increases rapidly within the first 48 hours, dropping to ambient temperature after that period. The measured temperature of both concrete decks and steel girders were near the ambient temperature within 48 hours of placement. In general, steel girders expand more than the bridge deck as the ambient temperature increases, inducing the tensile stresses in the concrete deck. Heating the air below the steel girders can increase the girder temperature in cold weather and reduce the effect of temperature differences between concrete decks and steel girders at early ages (Durability 1970, Babaei and Fouladgar 1997).

Babaei and Purvis (1996) analyzed thermal and drying shrinkage of concrete samples taken during the construction of eight bridges and recommended that drying shrinkage within the four months of concrete placement should be limited to 700 $\mu\varepsilon$ to obtain a transverse crack spacing of at least 30 ft (9 m). Thermal shrinkage should also be less than 150 $\mu\varepsilon$. That can be achieved by minimizing the temperature difference between the concrete and the steel girders to a maximum of 22° F (12° C).

1.4.3 Curing Conditions

Curing procedures have a significant effect on the development of early age plastic shrinkage cracking; proper curing techniques after finishing can reduce these types of plastic concrete cracking. Holt (2001) studied the effect of different curing conditions on the development of early age shrinkage; the study included three different curing conditions during the first 24 hours after casting, as labeled in Figure 1.6: wind (4.5 mph [2 m/s] speed), dry (40 percent relative humidity), and wet (100 percent relative humidity). Holt (2001) did not indicate the value of the relative humidity for the specimens subjected to wind. As shown in Figure 1.6, high shrinkage was observed for the specimens exposed to wind, with lower shrinkage for specimens subjected to dry conditions, and the least shrinkage for specimens subjected to wet conditions. The amount of shrinkage due to drying between the end of curing, at 24 hours, and the end of the test, at 65 days, was the same for the three methods of curing.

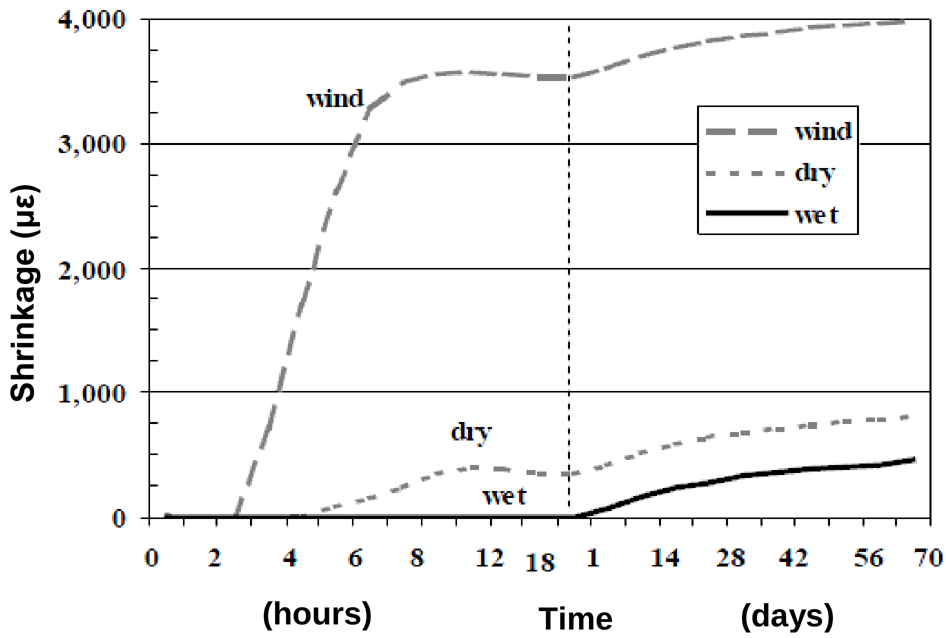


Figure 1.6: Effect of curing conditions on the early age shrinkage of concrete (Holt 2001).

Nassif and Suksawang (2002) studied the effects of six curing methods on the shrinkage of concrete specimens. The methods evaluated were dry curing, moist curing with 95 percent relative humidity, curing with the application of a curing compound, and curing with the application of wet burlap for three periods: 3, 7, and 14 days. The least shrinkage was experienced by specimens with wet curing at 95 percent relative humidity, with progressively greater shrinkage experienced by specimens cured with wet burlap for 14, 7, and 3 days (more shrinkage was observed for specimens cured for shorter period), curing compound, and dry curing, having the greatest shrinkage of all.

Yuan et al. (2011) analyzed the free shrinkage of two sets of mixtures; the cementitious material was composed of 100 percent portland cement in the first set, and 60 percent portland cement and 40 percent fly ash by volume in the second set. Increasing the curing period decreased the free shrinkage of both sets of mixtures. However, a longer curing period was more beneficial for mixtures containing cement and fly ash than the mixture with the 100 percent of cement. For the mixture containing 40 percent fly ash, more free shrinkage was observed than the 100 percent cement mixture when cured for 7 days; at 14 days curing, similar shrinkage was observed for both mixtures, and less shrinkage was observed for the mixture containing fly ash when specimens were cured for 28 or 56 days.

As Lindquist et al. (2008) observed, increasing the curing period from 7 to 14 days decreases the free shrinkage for a mixture with a constant paste content and water-cement ratio. Increasing the curing period from 7 to 21 days is more beneficial at reducing shrinkage than decreasing the paste content.

1.4.4 Finishing

Overfinishing a deck brings excess cement paste to the surface (Pendergrass and Darwin 2014). Moreover, overfinishing and overwetting the surface of bridge decks increases spalling (Larson et al. 1967) and scaling of the deck surface (Klieger 1955). Overfinishing also leads to a prolonged period of time until the initiation of curing and therefore subjects the deck to more plastic shrinkage cracking (Pendergrass and Darwin 2014). The method of finishing is also important; Lindquist et al. (2005) stated that roller screeds bring more paste to the deck surface than vibrating screeds, resulting in durability problems.

1.4.5 Structural Design

Cracking of bridge decks is also affected by the structural design of the bridge. As the degree of restraint between deck and girders increases, cracking of the deck also increases. Fully restrained bridge decks experience higher cracking because the restraint limits shrinkage and expansion in the deck. A partially restrained bridge deck allows partial strain in concrete before stresses develop and, thus, reduces cracking (Krauss and Rogalla 1996).

The placement of reinforcement in the bridge deck can also reduce cracking. ACI 345 recommends placing the longitudinal reinforcement above the transverse reinforcement as a means to reduce transverse cracking (ACI Committee 345, Babaei and Purvis 1994), although longitudinal reinforcement is rarely used as the outer layer.

Some studies have suggested that cracking increases in continuous spans compared to simple spans (Krauss and Rogalla 1996, Ramey et al. 1996, Ramey and Wright 1994). These studies found that cracking in continuous spans occurs in the negative moment regions above the piers where the deck is at tension (Ramey et al. 1996, Ramey and Wright 1994). In contrast, other researchers have found relatively little increase in cracking in the negative moment regions compared to that observed in the other regions of bridge decks (Lindquist et al. 2005, Pendergrass et al. 2011, Yuan et al. 2011).

Some studies have found an increase in cracking tendency for bridges with steel girders compared to bridge with concrete girders (Durability 1970, Ramey et al. 1996, Ramey and Wright 1994). The reason for this observation can be related to the flexibility, longer spans, lack of creep, and higher difference in thermal expansion coefficient of steel girders compared to concrete girders (Pendergrass and Darwin 2014).

Many researchers have studied the effect of span length on cracking of bridge decks. Krauss and Rogalla (1996) observed that longer spans, which usually have larger girder sections, exhibit more cracking in the deck because of the higher shrinkage and thermal stresses developed with the restraint provided by larger girder sections. In contrast, Schmitt and Darwin (1995), Miller and Darwin (2000), and Lindquist et al. (2005) observed no effect of span length on bridge deck cracking. Horn et al. (1972) found that slab thickness has an effect on the cracking tendency of bridge decks and observed less cracking on bridges with 8.6 in. (218 mm) deck thickness compared to those with a 6.4 in. (162 mm) deck thickness.

1.5 Low Cracking – High Performance Concrete Bridge Decks

The low-cracking high-performance concrete (LC-HPC) specifications are special provisions to the Kansas Department of Transportation (KDOT) standard specifications. These specifications have been adjusted and improved over time based on laboratory test results and field evaluations to yield more durable bridge decks with less cracking. The LC-HPC specifications cover aggregate, concrete, and construction methods.

1.5.1 Aggregate

The LC-HPC specifications require a maximum aggregate size of 1 in. (25 mm) and an optimized combined aggregate gradation to improve concrete workability. The proportioning of the combined aggregate can be done using the Shilstone Method (1990) or KU Mix Method (Lindquist et al. 2008). Table 1.1 shows the allowable limits for the gradation of the combined aggregate.

Table 1.1: LC-HPC combined aggregate gradation limits.

Percent Retained on Individual Sieve-Square Mesh Sieve										
Usage	1 in. (25.0 mm)	3/4 in. (19.0 mm)	1/2 in. (12.5 mm)	3/8 in. (9.5 mm)	No.4 (4.75 mm)	No.8 (2.39 mm)	No.16 (1.18 mm)	No.30 (600 µm)	No. 50 (300 µm)	No. 100 (150 µm)
LC-HPC Bridge Decks	2 to 6	5 to 18	5 to 18	5 to 18	5 to 18	5 to 18	5 to 18	8 to 15	5 to 15	0 to 15

The coarse aggregate can be gravel, crushed stone or chat with a minimum soundness of 0.9 and a maximum absorption of 0.7 percent. Table 1.2 shows the maximum allowable limits for deleterious substances in coarse aggregate. The fine aggregate can be natural sand (Type FA-A) or chat (Type FA-B). Table 1.3 shows the maximum allowable limits for deleterious substances in both types of fine aggregate.

Table 1.2: Maximum allowable limits for deleterious substances in coarse aggregate.

Substance	Maximum Allowable (by Weight)
Material passing No. 200 sieve	2.5%
Shale or shale-like material	0.5%
Clay lumps and friable particles	1.0%
Sticks (including absorbed water)	0.1%
Coal	0.5%

Table 1.3: Maximum allowable limits for deleterious substances in fine aggregate.

Natural Sand	
Substance	Maximum Allowable (by Weight)
Material passing No. 200 sieve	2.00%
Shale or shale-like material	0.50%
Clay lumps and friable particles	1.00%
Sticks (including absorbed water)	0.10%
Chat	
Substance	Maximum Allowable (by Weight)
Material passing No. 200 sieve	2.00%
Clay lumps and friable particles	0.25%

1.5.2 Concrete

The current LC-HPC specifications require a cementitious material content range of 500 to 540 lb/yd^3 (270 to 320 kg/m^3) with a water-cementitious material ratio ranging between 0.44 and 0.45 (by weight). The specifications allow a water-cement ratio of 0.43 with the approval of the engineer. The air content range is between 7.0 and 9.0 percent (by volume) with an allowable tolerance of 0.5 percent. The slump range of plastic concrete is 1.5 to 3.0 in. (40 to 75 mm) at the point of placement; any concrete with a slump more than 3.5 in. (90 mm) must be rejected by the engineer. Samples for air content and slump tests must be taken at the discharge end of the bucket, conveyor, or pump piping. The twenty eight-day compressive strength must be between 3500 and 5500 psi (24.1 to 37.9 MPa). The temperature of concrete must be taken immediately before placement and may be between 55º to 70º F (13º to 21º C) with allowance of 5º F (3º C) below or above that range if approved by the engineer.

The concrete supplier must produce a qualification batch before bridge construction to demonstrate the ability to produce concrete that meets the specified properties. The same equipment to be used for the actual bridge deck construction should be used for the qualification batch. Moreover, the transportation time needs to be simulated to reflect the actual time before discharge of the qualification batch. If all of the stated limits are met, the concrete can be used as LC-HPC for bridge deck construction.

1.5.3 Construction

The engineer must measure and record wind speed, air temperature, and relative humidity at a distance of 12 in. (305 mm) above the surface of the deck. In addition, the concrete temperature needs to be measured and recorded at least once every hour during deck placement to determine the rate of evaporation, which needs to be below 0.2 $lb/ft^2/hr$ (1.0 $kg/m^2/hr$). When the rate of evaporation exceeds that limit, actions need to be taken to minimize evaporation, such as installing wind breaks or cooling the concrete temperature.

Consolidation of concrete needs to be performed using gang-mounted internal vibrators wherever possible on the deck surface and hand-held vibrators elsewhere. Vibrators must have the following specifications: head diameter between 1.75 and 2.5 in. (45 and 65 mm), vibration frequency between 8000 and 12000 vibrations per minute, and average amplitude of 0.025 to 0.05 in. (0.635 to 1.27 mm). Vibrators must be inserted and extracted slowly and vertically to avoid the formation of voids. Vibrators must also be spaced at 12 in. (305 mm) and held in the concrete between 3 and 15 seconds.

Once consolidation is complete, strike-off of the deck surface needs to be done using a single-drum roller screed or a vibrating screed. A burlap drag, metal pan, or both may be mounted on the finishing equipment to finish the deck surface. Bullfloating or hand floating may be used to remove irregularities in the surface, if needed. Finishing aids are prohibited.

Curing of LC-HPC includes the application of one layer of presoaked burlap within 10 minutes of strike-off. An additional layer of presoaked burlap must be placed within 5 minutes of the first layer. The burlap must be presoaked for at least 12 hours before the deck placement and must remain wet for a 14-day curing period. Fogging equipment or misting hoses can be used to maintain the burlap in a saturated state. White plastic sheeting must be placed over the burlap after the concrete has set and soaker hoses have been placed on the burlap to minimize evaporation from the burlap. Saturation of the burlap during the curing needs to be checked every six hours.

To ensure that both of the concrete supplier and the contractor are able to produce and construct the LC-HPC bridge deck, a qualification slab is constructed before the actual placement of the bridge deck using the same equipment, mix design, ready-mix plant and workers that will be used during construction. The qualification slab is accepted if the placement, consolidation, finishing, and curing requirements are satisfied.

1.6 Technologies to Minimize Settlement Cracking in LC-HPC Bridge Decks

As discussed in Section 1.3.1.1, settlement cracking occurs because of the settlement of plastic concrete above fixed objects, such as reinforcing bars. As plastic concrete settles, cracks that are directly above and parallel to the reinforcing bars start to form because of the extremely low concrete tensile strength at early ages. Additions such as fibers or admixtures such as rheology modifiers may reduce the potential for settlement cracking by enhancing the tensile strength, increasing the cohesiveness, or decreasing the bleed water within the plastic concrete. Researchers have found that the primary factors that affect the formation of settlement cracks are cover thickness, concrete slump, and reinforcing bar size (Dakhil et al. 1975, Babaei and Fouladgar 1997). Figure 1.7 illustrates an increase in the settlement cracking with decreased cover thickness, increased slump, and increased reinforcing bar size (Dakhil et al. 1975). These findings were confirmed by Darwin et al. (2004) and Lindquist et al. (2005), who observed an increase in crack density on bridge decks as slump increased from 1.5 to 3 in. (40 to 75 mm).

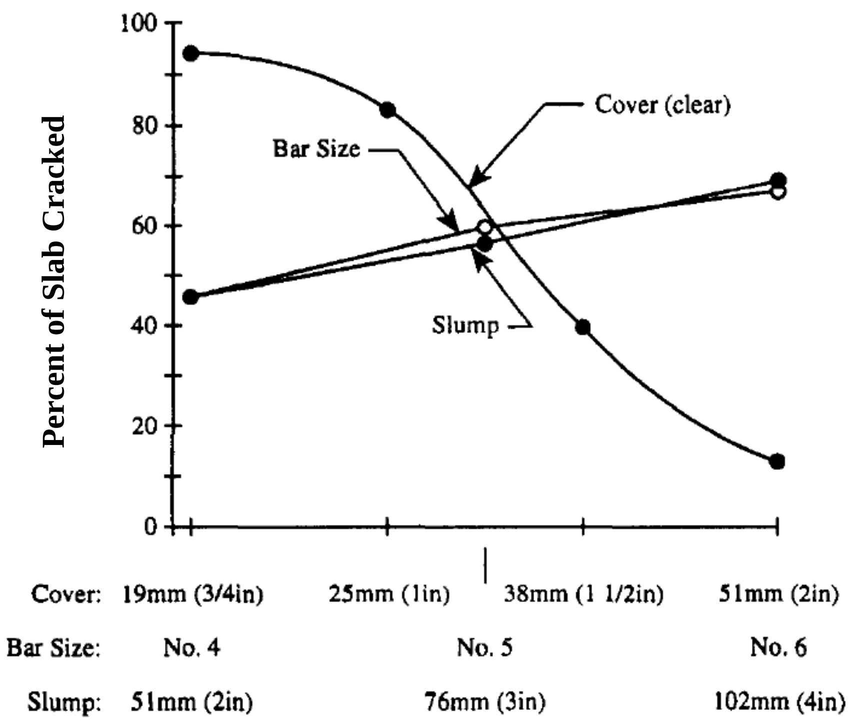


Figure 1.7: The effect of cover depth, concrete slump, and reinforcing bar size on settlement cracking (Dakhil, Cady, and Carrier 1975).

Some evidence exists that indicates that the use of synthetic polymer fibers may reduce settlement cracking. Although they provided no evidence, Suprenant and Malisch (1999) suggested that fibers can reduce the settlement cracking by reducing the amount of bleed water. Viscosity modifiers may increase the stability of plastic concrete by reducing the amount of bleed water and increasing the cohesiveness of the concrete. These properties may reduce the settlement of the plastic concrete and reduce the amount of settlement cracking.

1.6.1 Previous Work about Settlement Cracking

Dakhil, Cady, and Carrier (1975) studied the effect of concrete slump, depth of cover, and reinforcing bar size on settlement cracking of plastic concrete. The study included three concrete slumps, three cover depths, and three reinforcing bar sizes. Three specimens were tested for each set of variables, resulting in a total of 108 specimens. Slumps of 2, 3, and 4 in. (50, 70, and 100 mm), concrete covers of 0.75, 1.5, and 2 in. (19, 25, 38, and 51 mm), and bar sizes of No. 4, No. 5, and No. 6 (13, 16, and 19 mm) were investigated to reflect the range of values typically found in bridge decks. 12×12×8 in. (305×305×203 mm) molds were used to cast concrete with a bar attached at each mold at the desired depth by fabricating holes on the mold sides. All specimens were vibrated using a 1 in. (25.4 mm) electrical vibrator, screeded parallel to the orientation of the reinforcing bar, and finished using a wet burlap drag. Decreasing the concrete cover, decreasing the bar size, and using a higher concrete slump led to increased settlement cracking.

In their study, Dakhil, Cady, and Carrier (1975) also investigated the effect of the presence of cracks on the corrosion of reinforcing bars. The corrosion study included specimens with No.5 reinforcing bars and 0.75 and 1.5 in. (20 and 40 mm) slump. Specimens were moist-cured for a week and then air dried in the laboratory. After that, a five percent (by weight) sodium chloride (NaCl) solution was ponded on the surface of specimens. The researchers followed a method developed by Stratfull (1973) to determine of corrosion activity of the embedded steel bars, that is, steel is corroding when the half-cell potential with respect to a copper/copper sulfate electrode (CSE) is less than –0.35 volts, and not corroding when the potential is greater than –0.30 volts with respect to CSE. Cracked specimens experienced higher corrosion potentials than uncracked, illustrating that settlement cracking increases the corrosion potentials of embedded reinforcing bars.

Babaei and Fouladgar (1997) studied the types of cracking found in bridge deck – plastic shrinkage cracking, settlement cracking, thermal shrinkage cracking, drying shrinkage, and flexural cracking. Practical methods to minimize cracking in bridge decks were provided in this study. Similar to Dakhil et al. (1975), Babaei and Fouladgar considered concrete slump, cover thickness, and reinforcing bar size as the main factors affecting settlement cracking. The researchers linked settlement cracking increases with decreases in cover thickness, increases in slump, and increases in bar size. Babaei and Fouladgar felt that a relatively high cover, 2.5 in. (64 mm), coupled with a moderate slump, 4 in. (100 mm), might prevent settlement cracking in bridge decks as recommended in this study. They also stated that settlement of plastic concrete causes weakened planes above the upper reinforcing bars, and that cracking because of other factors, such as drying shrinkage, can later occur at these weakened planes. Babaei and Fouladgar suggested that alignment of top and bottom transverse reinforcing bars should be avoided in bridge decks when the upper transverse reinforcement is perpendicular to traffic to minimize the formation of cracking above the bars. Limiting the size of top transverse reinforcing bar to No. 5 (16 mm) was also suggested.

Suprenant and Malisch (1999) investigated the effect of synthetic fibers on the settlement cracking of plastic concrete. The study included a 4.5 in. (115 mm) and 5.5 in. (140 mm) slump; a 0.5 in. (13 mm), 0.75 in. (19 mm) , and 1 in. (25.4 mm) cover; and No. 6 and No. 8 (No. 19 and No. 25) reinforcing bars. A total of 72 specimens were tested, three of those were tested for each combination of variables. The molds had the same dimensions and they followed the procedure developed by Dakhil et al. (1975), with the exception that the concrete surface was floated after vibration and screeding and a burlap drag was not used. Half of the specimens did not contain fibers. The other half contained 1.25 lb/yd^3 (0.74 kg/m^3) of a fibrillated polypropylene fibers. A single ready-mix truck was used to deliver the concrete, and the fibers were added to the concrete in the truck after all control specimens were cast. This led to a 40-minute delay in casting the concrete that contained the fibers. Settlement cracks were observed in all of the non-fiber specimens and no settlement cracks were observed in the specimens containing fibers, even under severe conditions (5.5 in. [140 mm] slump, 0.5 in. [13 mm] cover, and No. 8 reinforcing bars). It was concluded that fibers eliminated the formation of settlement cracking by increasing the tensile strength and reducing the bleed water of the fresh concrete. However, the 40-minute delay before adding the fibers to the concrete may have altered the results.

Combrinck and Boshoff (2013) studied how settlement cracking develops in concrete and the effect of revibration on the formation of settlement cracks. Two L-shaped molds consisting of deep and shallow sections were used to ensure differential settlement of plastic concrete. Transparent sides were used to allow the observation of any cracking below the concrete surface. The surfaces of the specimens were kept wet and cured in an environmentally controlled laboratory to prevent plastic shrinkage cracking. Both L-shaped specimens consisting of deep and shallow sections experienced hairline cracking at the boundary between the shallow and deep sections. One of the specimens experienced cracking below the surface. Based on that observation, the researchers determined that the plastic cracks forms from the bottom and spreads upward. This observation was confirmed using numerical analysis.

Combrinck and Boshoff (2013) recommended the use of revibration before final setting to reduce the settlement of concrete around reinforcing bars. To observe the influence of revibration on the concrete strength, two sets of concrete cubes were tested. The first set was revibrated at initial setting while the second set was revibrated at final setting. The results showed that revibrating concrete cubes at initial setting increases the strength while revibrating at final setting decreases the strength.

1.7 Objective and Scope

Slump, concrete cover, and reinforcing bar size are key variables that affect the development of settlement cracks in bridge decks. The first objective of this study was to develop a consistent test procedure to prepare, cure, and test concrete mixtures for settlement cracking. The second objective was to study the effect of potential crack reduction technologies, four types of synthetic fiber and a rheology modifier, on settlement cracking. For each series of tests, a minimum of 11 concrete batches, each with a different slump and with three settlement cracking specimens per batch, were tested. Settlement cracking was compared for mixtures with and without a crack reduction technology. The effect of the crack reduction technologies on the fresh concrete slump was also analyzed by testing the fresh concrete slump in accordance with ASTM C143 before and after adding the fibers or rheology modifier.

Chapter 2 EXPERIMENTAL PROGRAM

2.1 General

This chapter describes the laboratory work performed in this study. A total of 133 concrete batches were tested; for each batch, three settlement cracking specimens were cast. Three series of concrete mixtures were tested. The first series consisted of 27 control mixtures, denoted as Control-1, with 24.3 percent paste content and a water-to-cement ratio of 0.5. The temperature of the plastic concrete in the Control-1 mixtures ranged from 60 to 70° F (16 to 21° C). This series of mixtures was tested to observe the effect of concrete slump on settlement cracking. The second series consisted of 18 control mixtures, denoted as Control-2, with 27 percent paste content and a water-to-cement ratio of 0.45. The temperature of the plastic concrete in the Control-2 mixtures ranged from 61 to 71° F (16 to 22° C). This series of mixtures was tested to provide additional data about the effect of slump on settlement cracking. The third series consisted of 88 mixtures with 27 percent paste content and a water-to-cement ratio of 0.45. The temperature the plastic concrete in the third series ranged from 71 to 75° F (22 to 24° C). Fourteen mixtures in this series served as controls, denoted as Control-3, and were tested to provide additional data on the effect of slump on settlement cracking, observe the effect of fresh concrete temperature on settlement cracking performance by comparing the results of Control-2 and Control-3 mixtures, and serve as a basis of comparison for mixtures containing crack reduction technologies. The remaining 74 mixtures in this series were used to evaluate the effectiveness of a crack reduction technology on settlement cracking performance. Of those 74, 11 contained 3 lb/yd^3 (1.78 kg/yd^3) of F-1 fiber, 11 contained 7.5 lb/yd^3 (4.45 kg/m^3) of F-2 fiber, 12 contained 3 lb/yd^3 (1.78 kg/m^3) of F-3 fiber, 12 mixtures contained 1.5 lb/yd^3 (0.89 kg/m^3) of F-4 fiber, 11 mixtures contained 3 lb/yd^3 (1.78 kg/yd^3) of F-4 fiber, and 17 contained a rheology modifier in the form of a viscosity modifying admixture VMA-1 (dosed at 0.05% of mixture material dry weight). The fibers and admixtures used in this study are listed in Table 2.1. A full description of material properties is given in Section 2.2.

2.2 Materials

This section describes the properties of the materials used in this study.

2.2.1 Cement

Type I/II portland cement meeting the requirements of ASTM C150 was used in this study.

Table 2.1: Summary of fibers and admixtures used in this study.

Type of Material	Designation	Type	Material	Specific Gravity*	Tensile Strength*, ksi (MPa)	Aspect Ratio	Length, in. (mm)
Fiber	F-1	Macrofiber	Virgin copolymer/ Polypropylene	0.91	83-96 (570-660)	56	1.5 (38)
	F-2	Macrofiber	Virgin copolymer/ Polypropylene	0.91	83-96 (570-660)	79.5	2.25 (57)
	F-3	Macrofiber	Blend of polypropylene and polyethylene	0.92	90 (620)	90	1.6 (40)
	F-4	Microfiber	Fibrillated polypropylene	0.91	44 (300)	29	0.75 (19)
VMA	VMA-1	Viscosity Modifying Admixture	Hydrated Magnesium Aluminosilicate	N/A	N/A	N/A	N/A
AEA	AEA-1	Air-Entraining Admixture	Rosin-based	N/A	N/A	N/A	N/A
WRA	WRA-1	High-Range Water-Reducing Admixture	Propylene Oxide	N/A	N/A	N/A	N/A

* Values of specific gravity and tensile strength provided by manufacturers.

2.2.2 Fine Aggregate

Kansas River sand and pea gravel were used in this study as fine aggregate in all mixtures. The Kansas River sand had a specific gravity of 2.60, a fineness modulus of 2.94, and an absorption of 0.47%. The pea gravel had a specific gravity of 2.61, a fineness modulus of 4.79, and an absorption of 1.42%. The sieve analysis results of the sand and pea gravel are presented in Tables A.1 and A.2 in Appendix A.

2.2.3 Coarse Aggregate

Granite was used as the coarse aggregate in this study. Three gradations of granite, designated A, B, and C, were used to obtain a better gradation and improve the workability of the plastic concrete; Granite A had a maximum aggregate size (MSA) of 1.0 in. (25.0 mm), Granite B had a MSA of 0.75 in. (19 mm), and Granite C had a MSA of 0.5 in. (13 mm). All three had a specific gravity of 2.62 and an absorption of 0.58%. Granites A, B, and C had fineness moduli of 7.24, 7.01, and 6.62, respectively. The first 19 mixtures of this study (included in the Control-1 series) contained Granite A and Granite C as coarse aggregate, all other mixtures after that (eight mixtures of Control-1 and all mixtures of the second and third series) contained Granite B and Granite C as coarse aggregate. The reason switching from Granite A to Granite B was to eliminate any possible effect of large aggregate particles on the formation of settlement cracks, because the clear cover was just $1^1/_8$ in. (29 mm). This discussion will be illustrated in Chapter 3. The sieve analyses for Granite A, Granite B, and Granite C are presented in Tables A.3, A.4, and A.5 in Appendix A.

2.2.4 Fibers

Four types of fibers, designated F-1, F-2, F-3, and F-4, are examined in this study to evaluate their effectiveness in reducing settlement cracking. The properties of these fibers are described next.

2.2.4.1 F-1 and F-2 Fibers

F-1 and F-2 fibers, shown in Figures 2.1 and 2.2, are macro synthetic fibers consisting of twisted bundles made from Virgin Copolymer/Polypropylene. The producer of this type of fiber claims that F-1 and F-2 fibers reduce concrete shrinkage and improve its impact strength, fatigue resistance, and toughness. The properties of F-1 and F-2 fibers are presented in Table 2.1.

Figure 2.1: F-1 Fiber.

Figure 2.2: F-2 Fiber.

2.2.4.2 F-3 Fiber

F-3 fiber, shown in Figure 2.3, is a macro synthetic fiber (blend of polypropylene and polyethylene). The producer of F-3 fiber claims that it controls temperature and shrinkage cracking and adds toughness and impact and fatigue resistance to concrete. The properties of F-3 fiber are presented in Table 2.1.

Figure 2.3: F-3 fiber.

2.2.4.3 F-4 fiber

F-4 fiber, shown in Figure 2.4, is a micro fibrillated polypropylene fiber manufactured from virgin homopolymer polypropylene resins. The producer of F-4 fiber claims that it improves the cracking performance and fatigue resistance and reduces permeability. The properties of F-4 fiber are presented in Table 2.1.

Figure 2.4: F-4 fiber.

2.2.5 VMA-1

VMA-1 is a thixotropic anti-settling and rheology modifying agent consisting of a hydrous magnesium aluminum-silicate. VMA-1 may reduce settlement cracking by decreasing the amount of bleed water and increasing concrete stability and aggregate suspension in the fresh concrete matrix. Adding VMA-1 to concrete may reduce the plastic concrete slump. VMA-1, however, reduces the plastic concrete yield stress, which provides high flowability and pumpability, but maintains high stability for fresh concrete when the shear force is removed.

2.2.6 Concrete Mixtures

As described earlier, three series of mixtures with different paste contents and water-to cement-ratios were tested. A mix design program (KU Mix), developed at the University of Kansas, was used to optimize the aggregate gradations. Five aggregates were used to improve the concrete workability using the optimization program. Further discussion and information about aggregate optimization and the KU Mix program is presented by Lindquist et al. (2008, 2015). The

KU Mix program can be downloaded from https://iri.drupal.ku.edu/node/43. The mixture proportions for the Control-1, Control-2, and Control-3 series are presented in Tables 2.2 and 2.3 on a cubic yard saturated-surface-dry (SSD) basis. The volume of fibers used were calculated based on the total batch volume. VMA-1 was dosed at 0.05% of total mixture dry weight. Further discussion about concrete mixtures and their results will be presented in Chapter 3. The volume of the fibers, VMA, WRA, and AEA were not considered as materially altering the volume of the concrete.

Table 2.2: Mixture proportions of Control-1 mixtures, SSD cubic yard batch.

Material Type	Material	Quantity
Cement	Type I/II	500 lb
Water	---	250 lb
Aggregate 1	Granite A	453 lb
Aggregate 2	Granite C	893 lb
Aggregate 3	Pea Gravel	576 lb
Aggregate 4	Sand	1069 lb
WRA	WRA-1 (mL)	0 mL
AEA	AEA-1 (mL)	61 mL

Table 2.3: Mixture Proportions of Control-2 and Control-3 mixtures, SSD cubic yard batch.

Material Type	Material	Quantity
Cement	Type I/II	593 lb
Water	---	267 lb
Aggregate 1	Granite B	636 lb
Aggregate 2	Granite C	762 lb
Aggregate 3	Pea Gravel	629 lb
Aggregate 4	Sand	837 lb
WRA	WRA-1 (mL)	420 mL
AEA	AEA-1 (mL)	61 mL

2.3 Experimental Methods

Test specimens, mixing and curing procedures, and test measurements are described in this section.

2.3.1 Specimen Molds

Settlement cracking specimens were 12 × 12 × 8 in. (305 × 305 × 203 mm) and cast using molds, shown in Figure 2.5. A 12-in. (305-mm) long No. 6 (No. 19) reinforcing bar was attached to the molds 1.5 in. (38 mm) from the top of the mold providing a nominal clear cover of $1^{1}/_{8}$ in. (29 mm). The relatively low cover was selected to obtain consistently reproducible, observable settlement cracking over a wide range of slumps. The ends of the bar were threaded and attached through holes in the molds using machine screws. The molds were made of 0.75 in. (19-mm) thick plywood. The edges of the molds were sealed with a white latex caulk and the internal surfaces were oiled prior to each mixture.

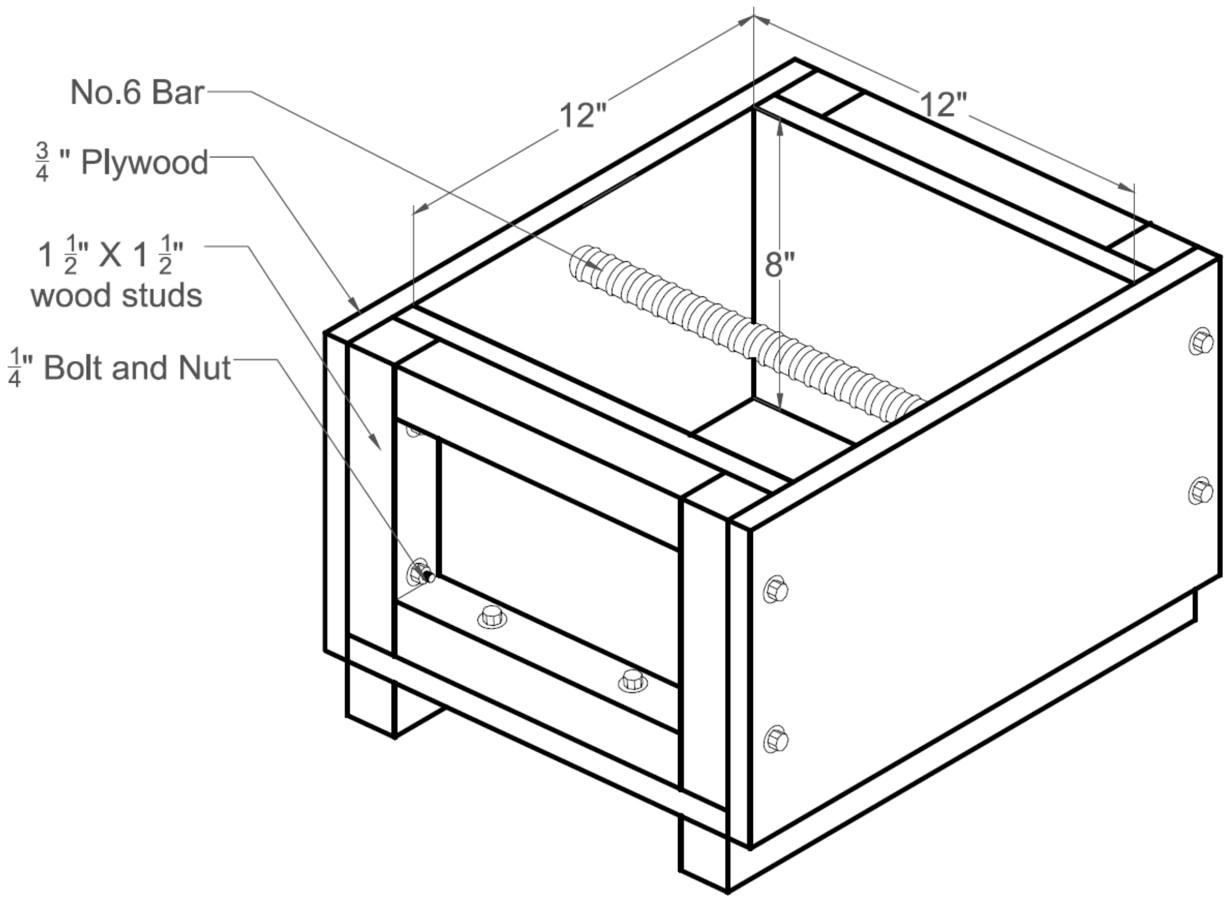


Figure 2.5: Settlement cracking mold.

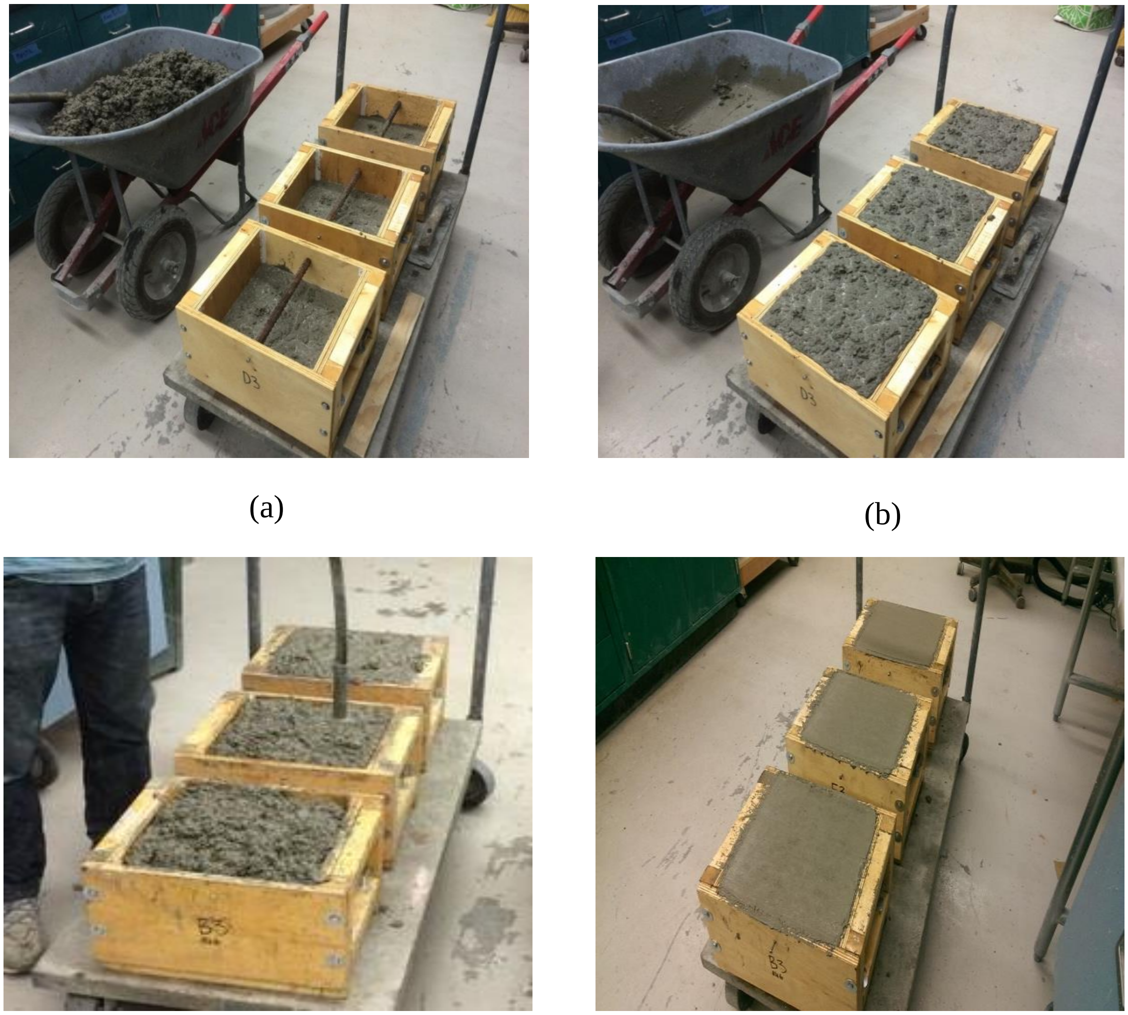
2.3.2 Mixing Procedure

A counter-current pan mixer was used in this study. Prior to mixing, the interior surface of the pan and the mixer paddles were dampened. The coarse aggregate and 80 percent of the mixture water were first added to the pan. The concrete temperature was controlled using hot water or ice, as needed. Cement was then added and the combination mixed for one and a half minutes. Sand and pea gravel were then added and concrete was mixed for two minutes. Ten percent of the mixture water, with the desired dosage of the high-range water-reducing admixture (WRA-1), was added to the mixer pan and mixed for one minute. The dosage of WRA-1 was varied, as needed, to obtain the desired slump. The final 10 percent of the mixture water, with air-entraining agent

(AEA-1), was then added and mixed for five minutes. The mixer was then turned off and the concrete was allowed to rest for five minutes. During the rest period, the concrete was covered with wet towels to minimize evaporation from the fresh concrete surface. After the rest period, the concrete was uncovered and mixed for three minutes. The fresh concrete temperature and slump were then determined in accordance with ASTM C1064 and ASTM C143, respectively. Air content was determined in accordance with ASTM C173 at least twice for each series of test to confirm that the air content was within the desired range (7.0-9.0 percent). For non-control mixtures, fibers or VMA were added at the desired dosage after taking the fresh concrete slump, and the concrete was mixed for 5 more minutes. After the five minutes of mixing, fresh concrete temperature and slump were measured again. The desired ranges of temperature and slump for each series of test were 65° F to 75° F (18° C to 24° C) and 2 in. to 8 in. (50 mm to 205 mm), respectively. Settlement cracking specimens were then cast and cured, as described in Sections 2.3.3 and 2.3.4, respectively.

2.3.3 Casting the Specimens

After measuring the fresh concrete temperature and slump, the concrete is transported to an environmentally controlled laboratory with a temperature of 73° ± 3° F (23° ± 1.5° C) and a relative humidity of 50 ± 4 percent. Specimens are filled in two layers of approximate equal depth (Figures 2.6a and 2.6b); each layer is vibrated using a $1^1/_8$-in. diameter cordless spud vibrator (Figure 2.6c). The surface is then finished using a wood screed and metal hand float (Figure 2.6d).



(a) (b) (c) (d)

Figure 2.6: Casting specimens: (a) half depth is filled and consolidated (b) second half is filled (c) consolidation of second layer (d) specimens after finishing.

2.3.4 Curing Procedure

The development of the test method used in this study is described by Brettmann, Darwin, and O'Reilly (2015); the final curing procedure is described below.

Specimens were cured by covering them with a 15 degree sloped Plexiglas plate enclosed in a layer of plastic sheeting. Enclosing the specimens provided sufficient humidity to eliminate plastic shrinkage cracking while allowing the settlement cracks to form. Specimens were cured for

24 hours in an environmentally controlled laboratory with a temperature of 73° ± 3° F (23° ± 1.5° C) and a relative humidity of 50 ± 4 percent. This procedure yielded consistent results without surface defects. Figure 2.7 shows the specimens during the curing period.

Figure 2.7: Settlement cracking specimens covered with sloped Plexiglas and plastic sheeting.

2.3.5 Settlement Cracking Reading

Settlement cracking readings were obtained after the specimens were cured for 24 hours in the environmentally controlled laboratory. Only cracks that were above and parallel to the reinforcing bar were considered settlement cracks. In few specimens, short cracks with a random orientation were observed around the perimeter of the upper surface of the specimen near the wooden form. These cracks had a width of less than 2 mils (0.002 in. [0.05 mm]) and were not counted as settlement cracks since they were remote from the reinforcing bar. Cracks were identified visually, without magnification; a flashlight was used to improve the visibility of narrow cracks. A black permanent marker was used to mark the settlement cracks. Marks were placed adjacent to the actual cracks to allow for subsequent measurement of the crack width, as shown in Figure 2.8. The intensity of cracking was then calculated by dividing the total length of cracks found on the specimen surface by the total length of the reinforcing bar (12 in. [305 mm]). The maximum width of each crack was measured using a crack comparator card. The average crack intensity of the three specimens was then considered as the crack intensity for the mixture. Crack length, width, and intensity for all mixtures are presented in Appendix B.

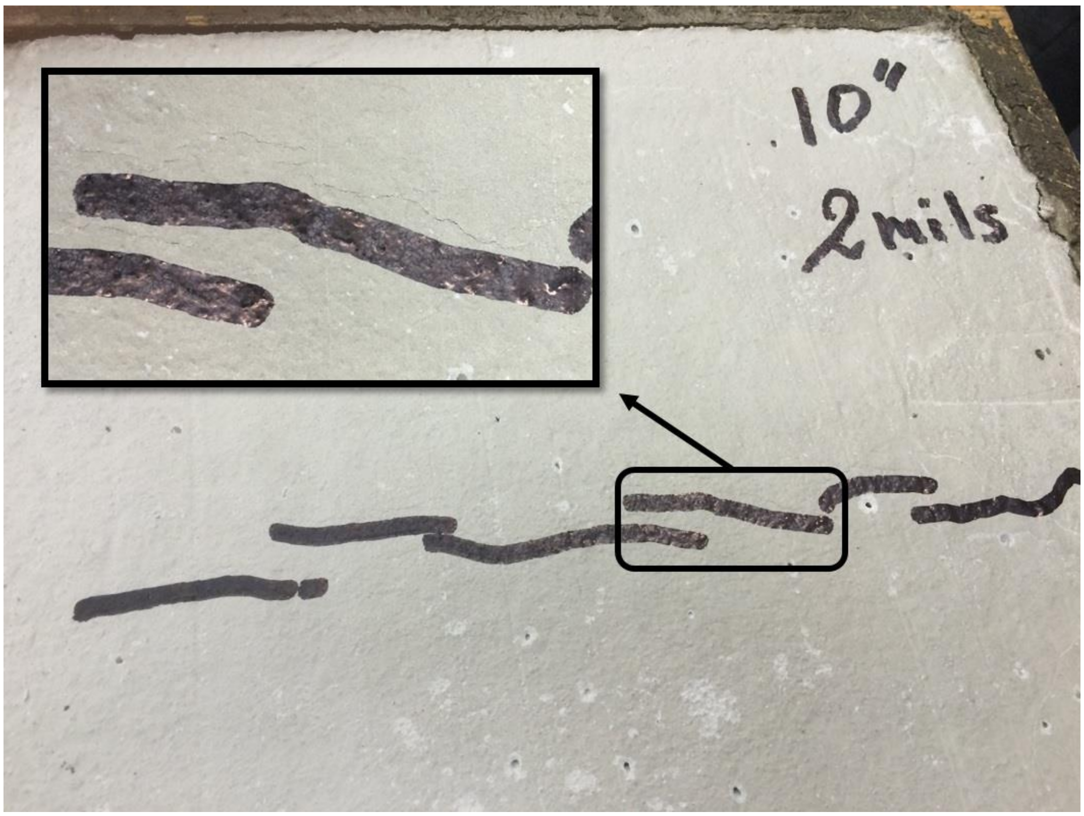


Figure 2.8: Settlement cracking reading.

2.4 Scope

This section summarizes the mixtures tested in this study. Three series of control mixtures, Control-1, Control-2, and Control-3, five series of fiber mixtures, F-1, F-2, F-3, and two dosages of F-4, and one series containing the viscosity modifying admixture VMA-1 were tested. The slump ranged from 1.25 to 9 in. (30 to 230 mm), air content ranged from 5.25 to 9.25%, and concrete temperature ranged from 60 to 77° F (16 to 25° C). Table 2.3 includes the ranges in slump, temperature, and air content of the individual series.

Table 2.4: Summary of Mixtures

System	Slump Range, in. (mm)	Percentage Air Range	Temperature Range, ° F (° C)
Control-1	1.25-9.0 (30-230)	8.5-9.25	60-70 (16-21)
Control-2	1.75-8.25 (45-210)	7.75-9.25	61-71 (16-22)
Control-3	2.25-7.75 (60-200)	6.75-7.00	71-75 (22-24)
3 lb/yd^3 (1.78 kg/m^3) F-1	2.75-8.25 (70-210)	8.0-8.75	73-74 (23)
7.5 lb/yd^3 (4.45 kg/m^3) F-2	2.75-8.0 (70-205)	7.75-9.25	72-75 (22-24)
3 lb/yd^3 (1.78 kg/m^3) F-3	2.5-8.5 (65-215)	6.0-8.75	73-75 (23-24)
1.5 lb/yd^3 (0.89 kg/m^3) F-4	2.75-8.25(70-210)	7.75-8.75	72-74 (22-23)
3 lb/yd^3 (1.78 kg/m^3) F-4	2.5-8.5 (65-215)	8.25	73-75 (23-24)
VMA-1	1.75-8.25 (45-210)	5.25-11.25	72-75 (22-24)

Chapter 3 RESULTS AND EVALUATION

3.1 General

This chapter presents the results of three series of specimens designed to evaluate the effect of slump and fresh concrete temperature, the addition of fibers, and the use of a rheology modifier in the form of a viscosity modifying admixture (VMA) on settlement cracking of plastic concrete. The first series, which included 27 control mixtures with a 24.3 percent paste content by volume of concrete and a water-to-cement ratio of 0.5, is denoted as Control-1. The second series, which included 18 control mixtures with a 27 percent paste content by volume of concrete and a water-to-cement ratio of 0.45, is denoted as Control-2. The third series, which included mixtures with a 27 percent paste content and a water-to-cement ratio of 0.45, included control mixtures (designated as Control-3) and mixtures containing either fibers or a VMA. The second and third series had a water-to-cement ratio of 0.45 to simulate concrete used in LC-HPC bridge decks; the paste content was increased from 24.3 to 27 percent to obtain more consistent results. Control-2 and Control-3 mixtures illustrated the effect of fresh concrete temperature on the settlement cracking performance by comparing the cracking performance at the same level of paste content and water-to-cement ratio, but different temperature range. Three settlement cracking specimens were cast for each batch of specimens. The cracking intensity for a specimen is calculated by dividing the total length of settlement cracks observed on the surface of the specimen by the length of the reinforcing bar (12 in. [305 mm]); only cracks that are above and parallel to the reinforcing bar are counted as settlement cracks. In few specimens, short cracks with a random orientation were observed around the perimeter of the upper surface of the specimen near the wooden form. These cracks had a width of less than 2 mils (0.002 in. [0.05 mm]) and were not counted as settlement cracks since they were remote from the reinforcing bar. The average crack intensity of the three specimens used as the crack intensity for that batch.

3.2 Series One

Figure 3.1 shows settlement crack intensity versus slump for mixture Control-1. Three lines are shown; a central trendline (showing the average of the data) and two lines offset 20% from the trendline. The 20% lines give an indication of the scatter in the data. Concrete slump ranged from 1.25 to 9 in. (30 to 230 mm) and crack intensity ranged from 0.08 to 0.88. Even though there was scatter in the data, it can be seen that settlement crack intensity increased as slump increased, with the average crack intensity increasing from 0.34 at a slump of 3 in. to 0.62 at a slump of 8 in. Half of the data fell within the upper and lower 20 percent lines. One mixture (slump of 1.25 in. [30 mm] and crack intensity of 0.79) could not be finished properly and was not used in calculating the trend line. Three additional properly finished mixtures with 1.25-in. (30-mm) slump were tested; the resulting crack intensities were 0.18, 0.21, and 0.23.

Some of the scatter found in this series is believed to be related to the fact that the first 19 mixtures of Control-1 (including the outlier mixture) contained Granite A, which had a 1 in. (25 mm) maximum size. Since the clear cover was only $1^1/_8$ in. (30 mm), the presence of large aggregate above the reinforcing bar likely affected the formation of settlement cracks, increasing the scatter. As described in Chapter 2, to overcome this problem, a new granite gradation, denoted Granite B, with a maximum size of 0.75 in (19 mm), replaced Granite A. All of the mixtures also contained an intermediate-size aggregate with a maximum size of 0.5 in (13 mm), denoted Granite C. As shown in Figure 3.1, 18 mixtures contained Granites A and C and eight mixtures contained Granites B and C. All batches in Series 2 and 3, discussed next.

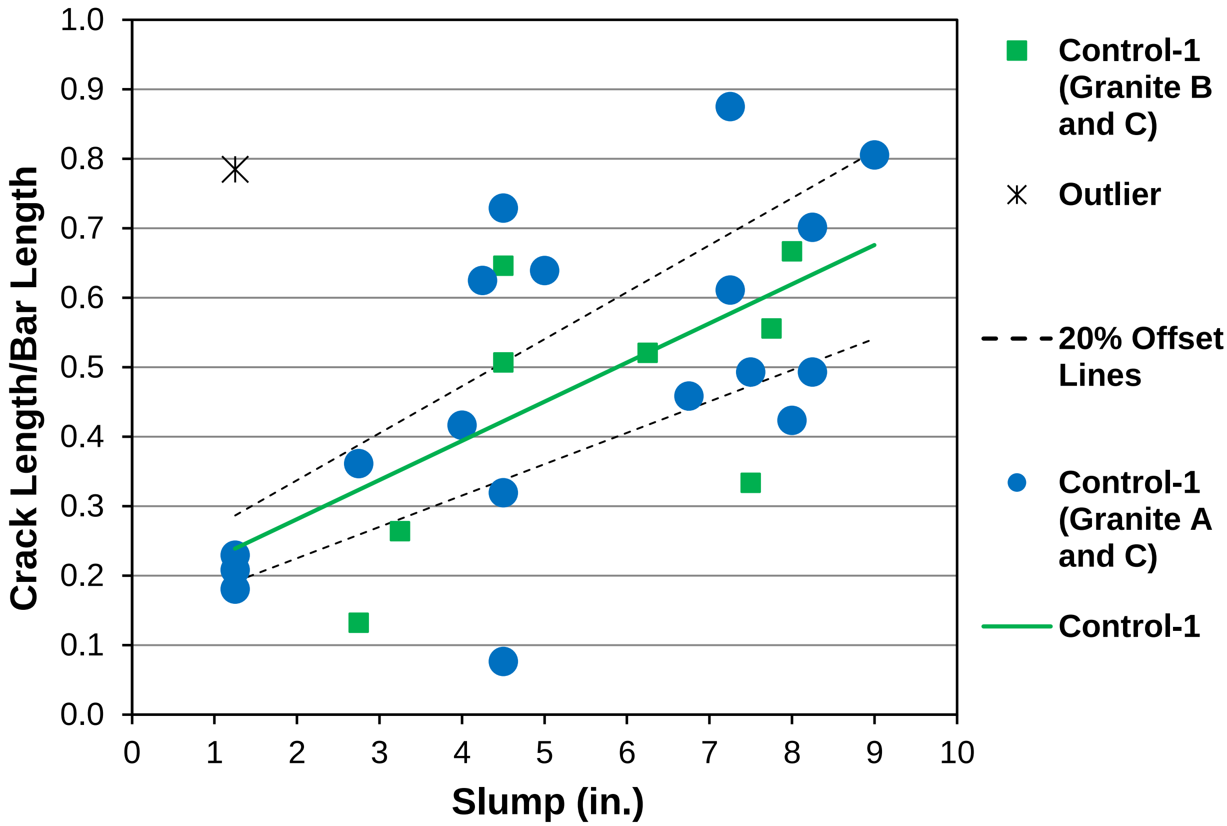


Figure 3.1: Settlement crack intensity versus slump for Control-1 mixtures.

3.4 Series Two

This series of tests included 18 control mixtures, denoted as Control-2. Tests of the Control-2 mixtures provided additional data on the effect of slump on settlement cracking.

Figure 3.2 shows settlement crack intensity versus slump for mixture Control-2. The slump ranged from 1.75 to 8.25 in. (45 to 210 mm) and the crack intensity ranged from 0.38 to 0.79. The trend is similar to that observed for the Control-1 mixtures, and in general, crack intensity increased as slump increased, with the average crack intensity increasing from 0.53 at a slump of 3 in. to 0.71 at a slump of 8 in. Crack intensities for 13 of the 18 mixtures fell within 20% of the average trendline.

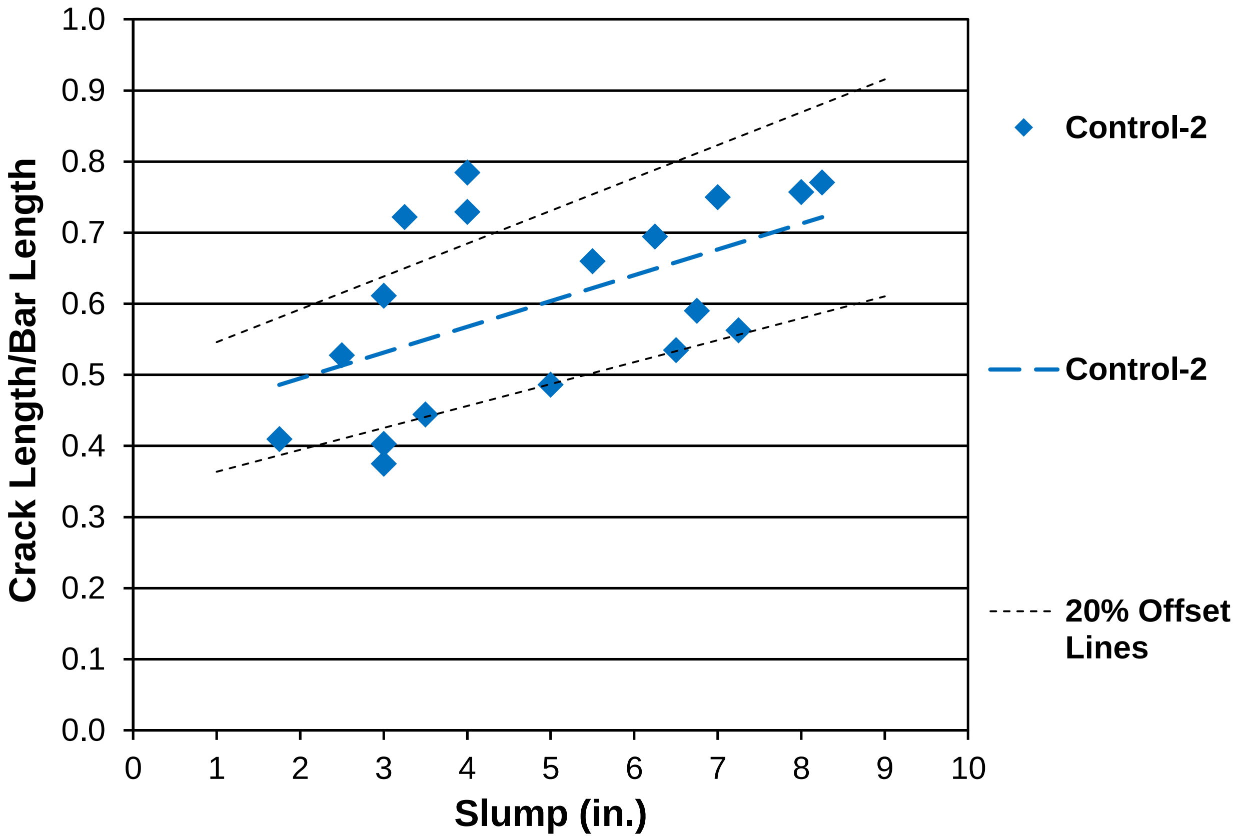


Figure 3.2: Settlement crack intensity versus slump for Control-2 mixtures.

Figure 3.3 compares settlement crack intensity for mixtures Control-1 and Control-2. There is some overlap in the data; however on average, Control-2 exhibited more cracking for a given slump. To determine the statistical significance of these differences, Student's t-test was used to compare the two series. The comparison was performed at slumps from 1 to 8 in. (25 to 200 mm) at 1-in. (25-mm) intervals. For each series, the average trend-line equation was derived based on the slump of the mixtures and the corresponding crack intensities. To calculate the t-value within slump intervals, the mean $\bar{x}$ of each slump interval, the standard deviations of the two series, and the number of samples of each series needed to be calculated. The mean $\bar{x}$ of each interval of slump was calculated using the average trendline equation derived for each series. The standard deviation was calculated by comparing the measured value of the cracking intensity x_i of each mixture to the cracking intensity $\overline{x}_i$ predicted for the slump of the mixture by the average trend line equation; that is:

$$\sigma = \sqrt{\frac{\sum_i (x_i - \overline{x}_i)^2}{n-1}}$$

Where σ= the standard deviation of a series, x_i = the cracking intensity of mixture i in the series, $\overline{x}_i$= the cracking intensity predicted by the trendline of the series at the slump of mixture i, and n = the number of batches in the series.

The t-value was then calculated using the appropriate equation for independent groups of unequal sample sizes. The level of significance α, which represents the probability that any apparent differences in the data sets are due to natural variability in the test program and not differences in the effectiveness of the evaluated crack control methods, was determined. Student's t-test shows these differences are statistically significant (α ranged from 6.85×10^{-6} to 0.046 over the slump range of 1 in. to 8 in. [25 to 205 mm]). The t-test results for all series tested are presented in Appendix C. The difference in the behavior of the two series is likely due to the different cement paste content. The Control-2 mixtures exhibited greater cracking compared to the Control-1 mixtures because the cement paste content in the Control-2 series was 2.7 percent higher than in the Control-1 series, suggesting that slump alone does not control settlement cracking. Both series, however, exhibited a similar trend, with increased slump leading to increased settlement cracking, an observation that agrees with those of Dakhil et al. (1975).

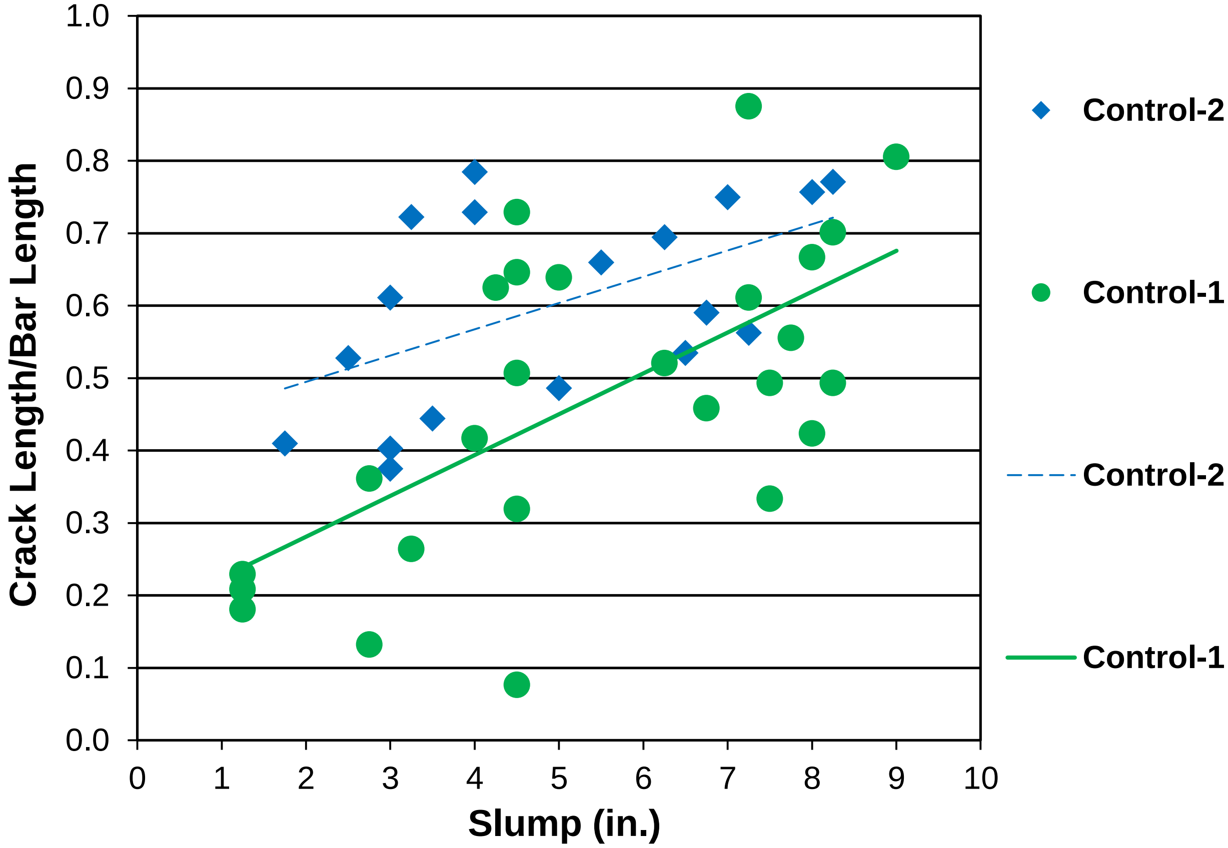


Figure 3.3: Settlement crack intensity versus slump for Control-1 and Control-2 mixtures.

3.4 Series Three

This series of tests included 14 control mixtures, denoted as Control-3, 11 mixtures containing 3 lb/yd^3 (1.78 kg/yd^3) of F-1 fiber, 11 mixtures containing 7.5 lb/yd^3 (4.45 kg/m^3) of F-2 fiber, 12 mixtures containing 3 lb/yd^3 (1.78 kg/m^3) of F-3 fiber, 12 mixtures containing 1.5 lb/yd^3 (0.89 kg/m^3) of F-4 fiber, 11 mixtures containing 3 lb/yd^3 (1.78 kg/yd^3) of F-4 fiber, and 17 mixtures containing VMA-1 (dosed at 0.05% of mixture material dry weight).

3.4.1 Control-3

Tests of the Control-3 mixtures provided additional data on the effect of slump on settlement cracking and formed a basis of comparison (at the same water-to-cement ratio, paste content, and fresh concrete temperature range) for mixtures containing fibers or VMA. The comparison between Control-2 and Control-3 mixtures illustrated the effect of fresh concrete temperature on settlement cracking performance.

Figure 3.4 shows settlement crack intensity versus slump for mixture Control-3. The slump ranged from 2.25 to 7.75 in. (60 to 200 mm) and the crack intensity ranged from 0.32 to 0.88. The trend is similar to that observed for the Control-1 and Control-2 mixtures, and in general, crack intensity increased as slump increased, with the average crack intensity increasing from 0.45 at a slump of 3 in. to 0.86 at a slump of 8 in. Crack intensities for 11 of the 14 mixtures fell within 20% of the average trendline.

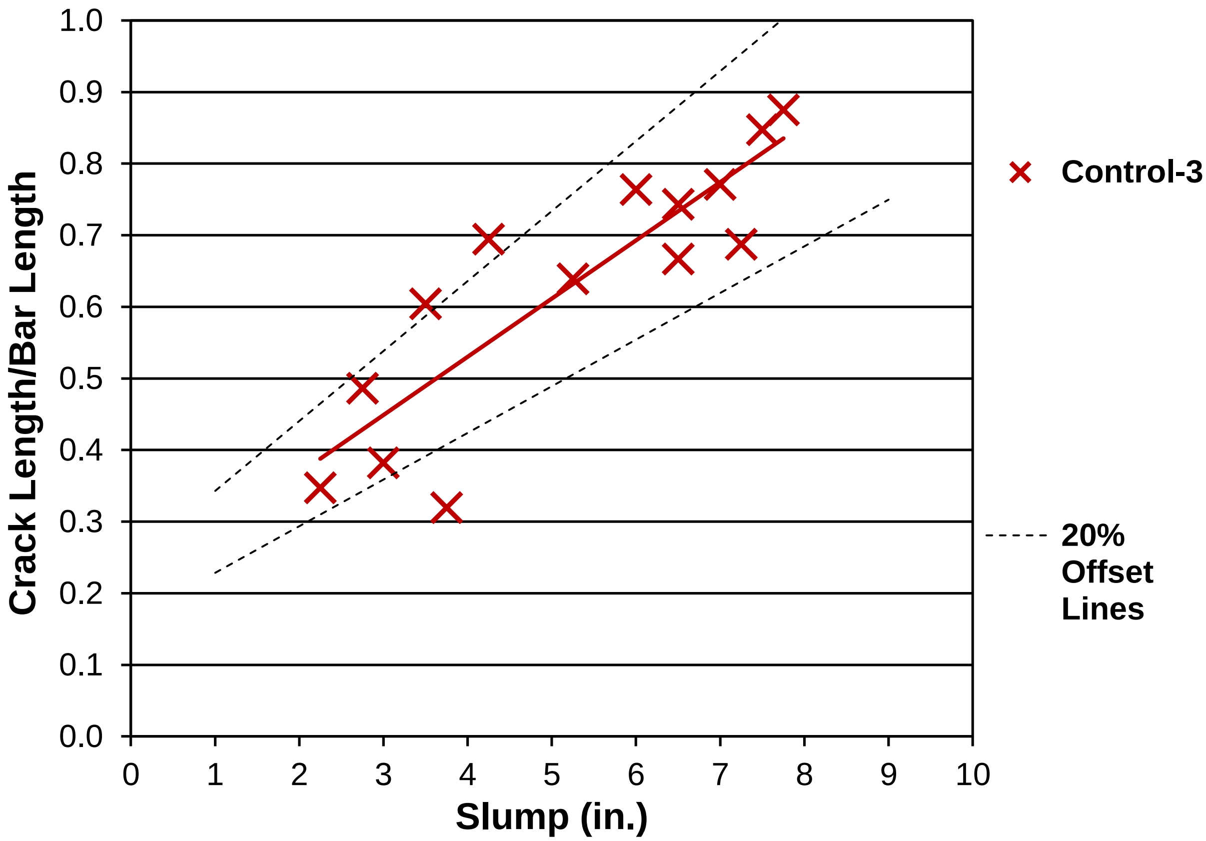


Figure 3.4: Settlement crack intensity versus slump for Control-3 mixtures.

Figure 3.5 shows settlement crack intensity for the Control-2 and Control-3 mixtures. There is overlap in the data. Control-2, on average, exhibited more cracking than Control-3 for low slump range (less than 4.5 in. [115 mm]). In contrast, Control-2 exhibited less cracking than Control-3 for high slump range (more than 4.5 in. [115 mm]). Student's t-test shows these differences are statistically significant for 1, 2, 3, 7, and 8 in. slump (α ranged from 6.41×10^{-5} to 0.000595 over the slump range of 1 to 8 in. [25 to 205 mm]).

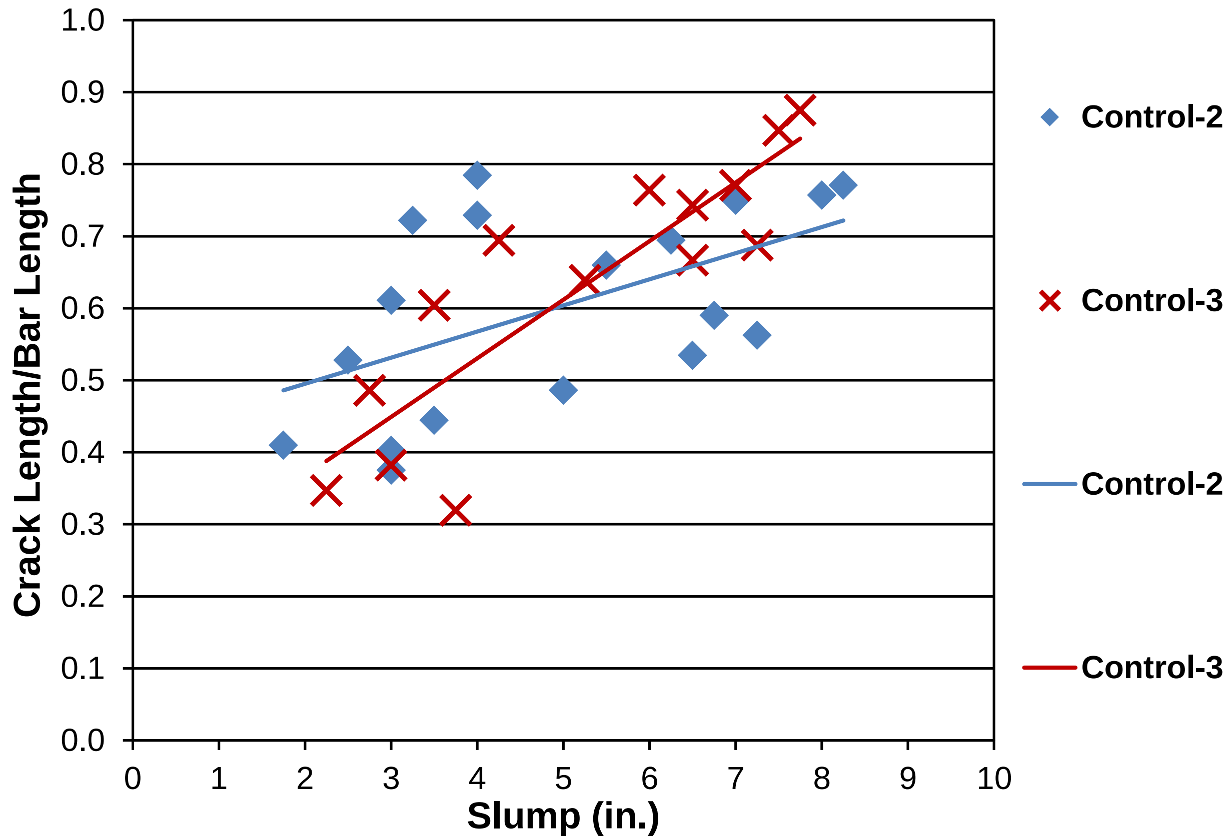


Figure 3.5: Settlement crack intensity versus slump for Control-2 and Control-3 mixtures.

3.4.2 F-1 fiber

Figure 3.6 shows settlement crack intensity versus slump for mixtures containing F-1 fiber. Eleven mixtures containing 3 lb/yd^3 (1.78 kg/m^3) of F-1 fiber were tested. The slump ranged from

2.75 to 8.25 in (70 to 210 mm) and the crack intensity ranged from 0.08 to 0.30. Average crack intensity increased from 0.15 at a slump of 3 in. to 0.27 at a slump of 8 in. The average reduction in slump after adding F-1 fiber was 2.25 in. (65 mm). Appendix D illustrates the decrease in slump due to the addition of the crack reducing additions for all series tested in greater detail. The slump values presented here are those obtained after adding F-1 fiber; slump values before the addition of F-1 fiber are presented in Appendix B.

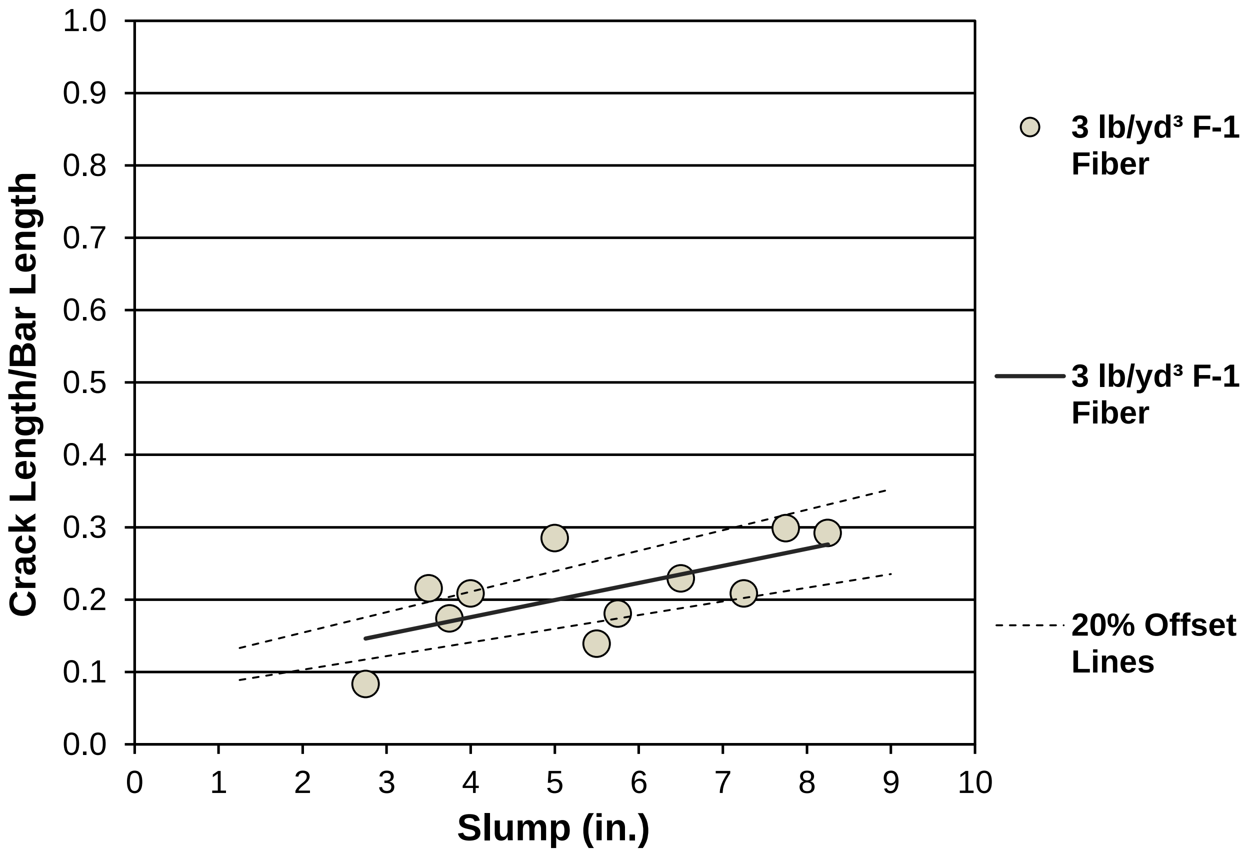


Figure 3.6: Settlement crack intensity versus slump for F-1 fiber mixtures.

Figure 3.7 shows settlement crack intensity for the F-1 fiber and Control-3 mixtures. The addition of F-1 fiber reduced cracking compared to control mixtures by reducing the bleeding water and improving the tensile strength of the fresh concrete surface. No overlap in the data is observed. The average reduction in the crack intensity between the Control-3 and F-1 fiber was

0.35 for a 4-in. (100 mm) slump. Student's t-test shows these differences are statistically significant (α ranged from 1.57×10^{-6} to 2.24×10^{-16} over the slump range of 1 to 8 in. [25 to 205 mm]).

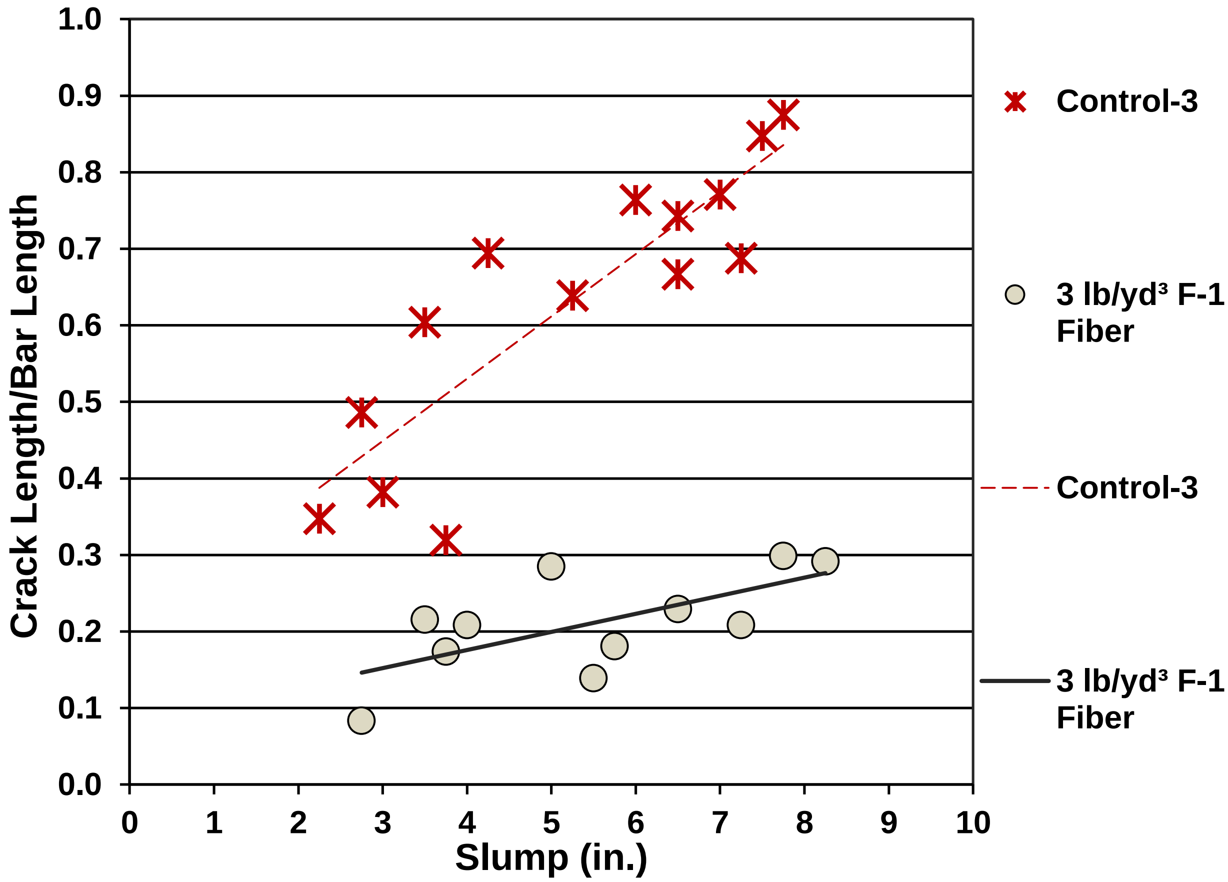


Figure 3.7: Settlement crack intensity versus slump for F-1 fiber and Control-3 mixtures.

3.4.3 F-2 Fiber

As described in Section 2.3.2, the concrete was first mixed for 16.5 minutes before the fibers were added to the mixer and mixed for 5 minutes. Even though this procedure yielded satisfactory distribution of most of the fibers tested, the F-2 fibers did not distribute well using this approach. The reason was likely due to the length of the F-2 fibers; the 2.2-in. (57-mm) fibers tended to stick to the mixer paddles, resulting in fewer fibers in the concrete matrix and a poor distribution. To overcome this problem, after the five minutes of mixing with the fibers the mixer was turned off, the fibers removed from the mixer paddles, and added back to the concrete. After this procedure, the concrete was mixed for an additional two minutes. Any remaining fibers on the paddles were removed from the mixer paddles, added to the concrete, and thoroughly mixed in by hand.

Figure 3.8 shows settlement crack intensity versus slump for mixtures containing F-2 fiber. Eleven mixtures containing 7.5 lb/yd^3 (4.45 kg/m^3) of F-2 fiber were tested. The slump ranged from 2.75 to 8.0 in. (70 to 205 mm), and the crack intensity ranged from 0.06 to 0.26. Average crack intensity increased from 0.10 at a slump of 3 in. to 0.23 at a slump of 8 in. The average reduction in slump after adding F-2 fiber was 4.0 in. (100 mm). This reduction in slump, greater than that of the other fibers tested, was likely due to the higher dosage of fiber used (7.5 lb/yd^3 [4.45 kg/m^3]). The slump values presented here are those obtained after adding F-2 fiber; slump values before the addition of F-2 fiber are presented in Appendix B.

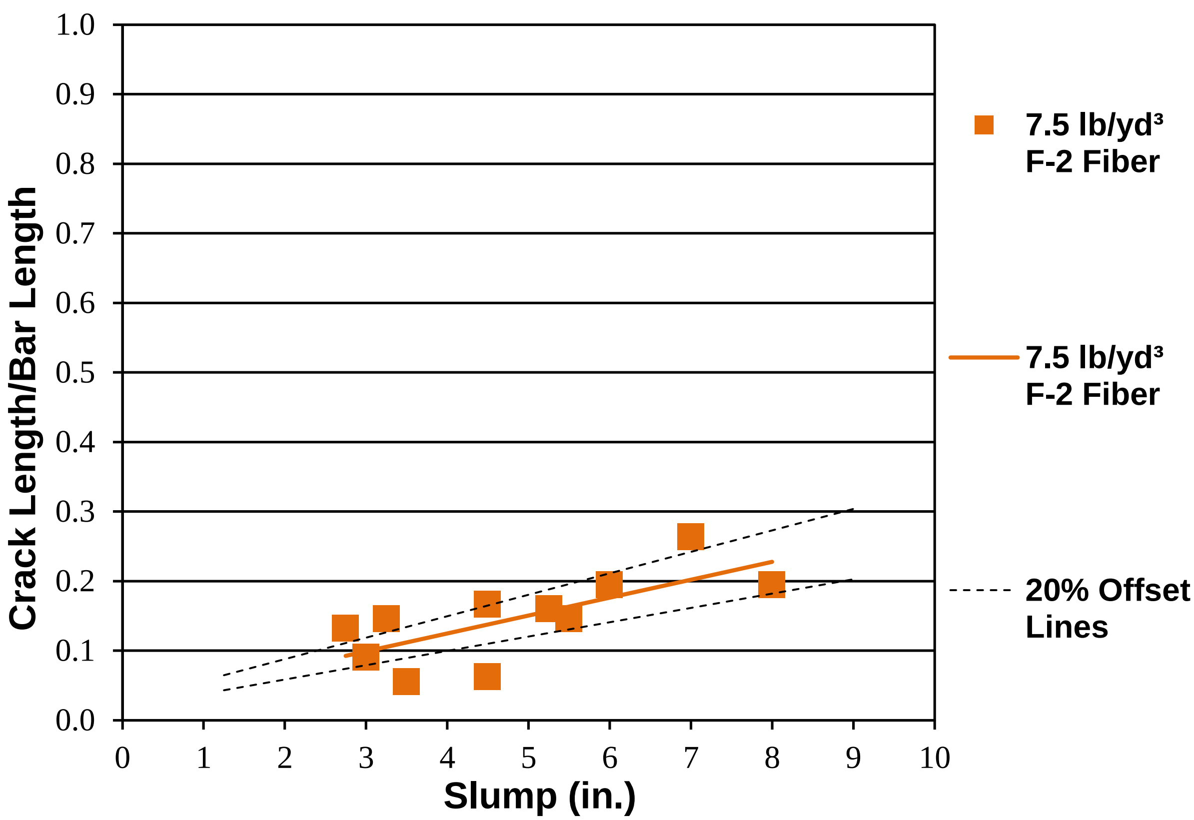


Figure 3.8: Settlement crack intensity versus slump for F-2 fiber mixtures.

Figure 3.9 shows settlement crack intensity for the F-2 fiber and Control-3 mixtures. The addition of 7.5 lb/yd^3 (4.5 kg/m^3) of F-2 fiber reduced cracking compared to control mixtures. No overlap in the data between the F-2 fiber and Control-3 mixtures was observed. The improved cracking performance of the F-2 fiber mixtures was likely due to the increased cohesiveness of the plastic concrete in addition to the reduction in bleed water because of the presence of the fibers in the plastic concrete matrix. The average reduction in the crack intensity between Control-3 and F-2 fiber was 0.41 for a 4-in. (100 mm) slump mixture. Student's t-test shows these differences are statistically significant (α ranged from 1.37×10^{-8} to 3.59×10^{-17} over the slump range of 1 to 8 in. [25 to 205 mm]).

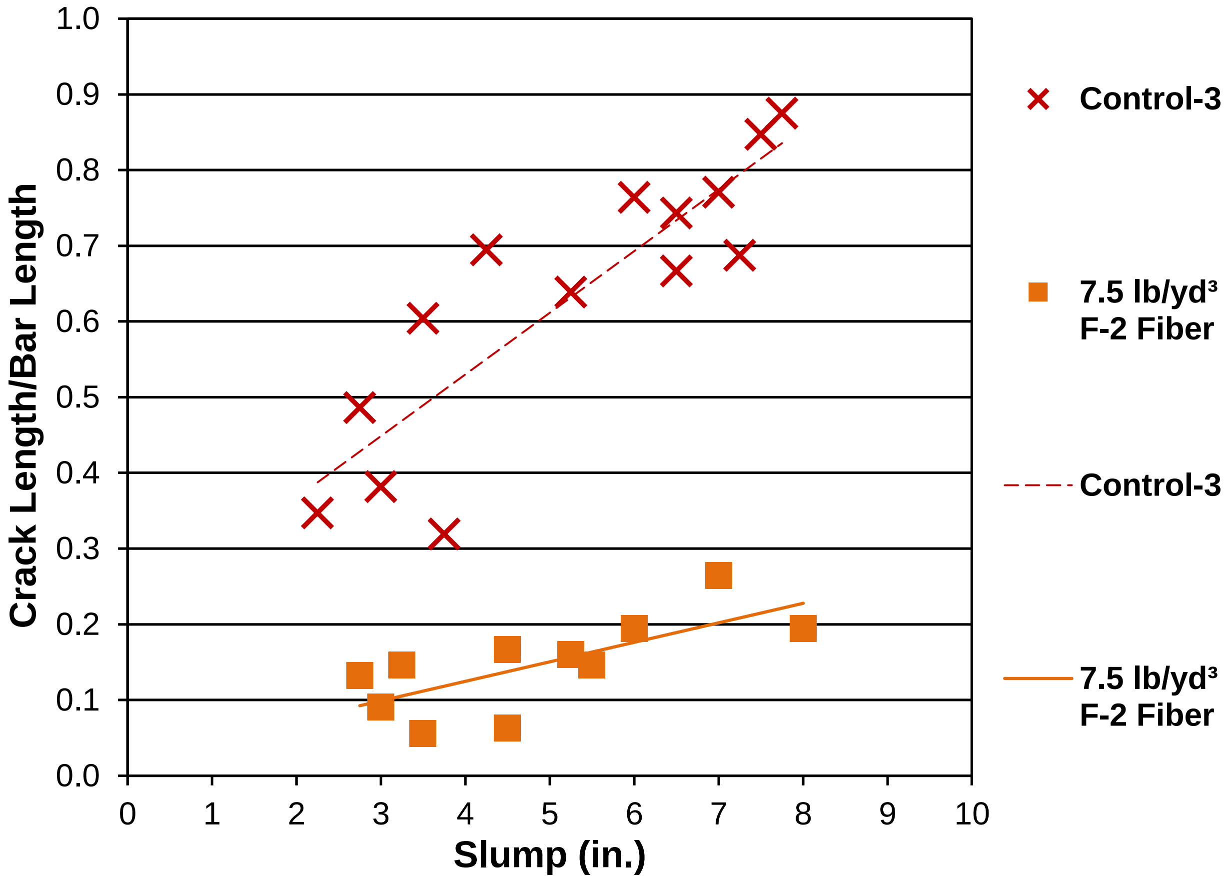


Figure 3.9: Settlement crack intensity versus slump for F-2 fiber and Control-3 mixtures.

3.4.4 F-3 Fiber

Figure 3.10 shows settlement crack intensity versus slump for mixtures containing F-3 fiber. Twelve mixtures containing 3 lb/yd^3 (1.78 kg/m^3) of F-3 fiber were tested. The slump ranged from 2.5 to 8.5 in. (65 to 215 mm), and the crack intensity ranged from 0.07 to 0.33. Average crack intensity increased from 0.13 at a slump of 3 in. to 0.26 at a slump of 8 in. The average reduction in slump after adding F-3 fiber was 1.5 in. (40 mm). The slump values presented here are those obtained after adding F-3 fiber; slump values before the addition of F-3 fiber are presented in Appendix B.

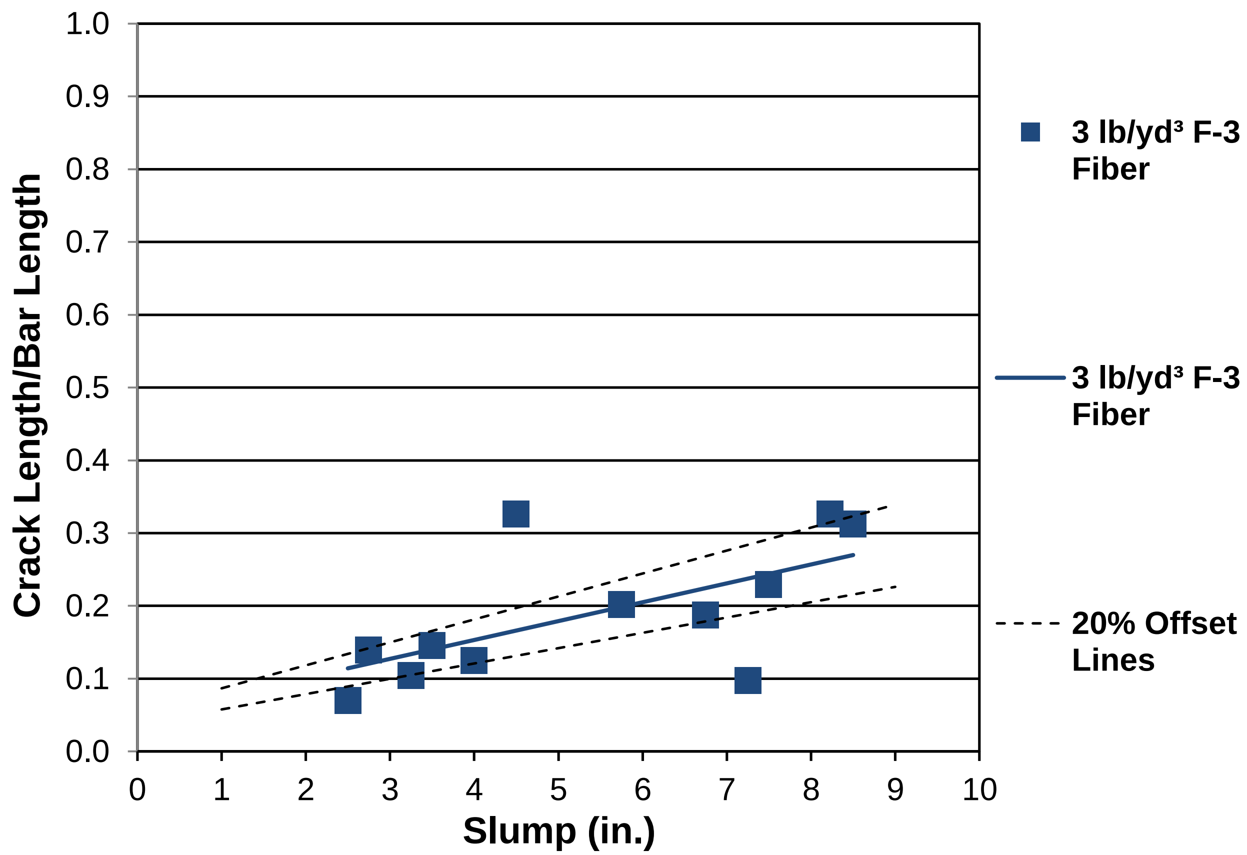


Figure 3.10: Settlement crack intensity versus slump for F-3 fiber mixtures.

Figure 3.11 shows settlement crack intensity for the F-3 fiber and Control-3 mixtures. The addition of F-3 fiber reduced settlement cracking compared to control mixtures. Like the other mixtures containing fiber, the improved cracking performance of F-3 fiber mixtures was likely due to the increased cohesiveness of the mixture in addition to the reduction in the bleeding water because of the presence of the fibers in the plastic concrete matrix. The average reduction in the crack intensity between the Control-3 and F-3 fiber was 0.38 for a 4-in. (100-mm) slump mixture. Student's t-test shows these differences are statistically significant (α ranged from 1.36×10^{-7} to 6.72×10^{-17} over the slump range of 1 to 8 in. [25 to 205 mm]).

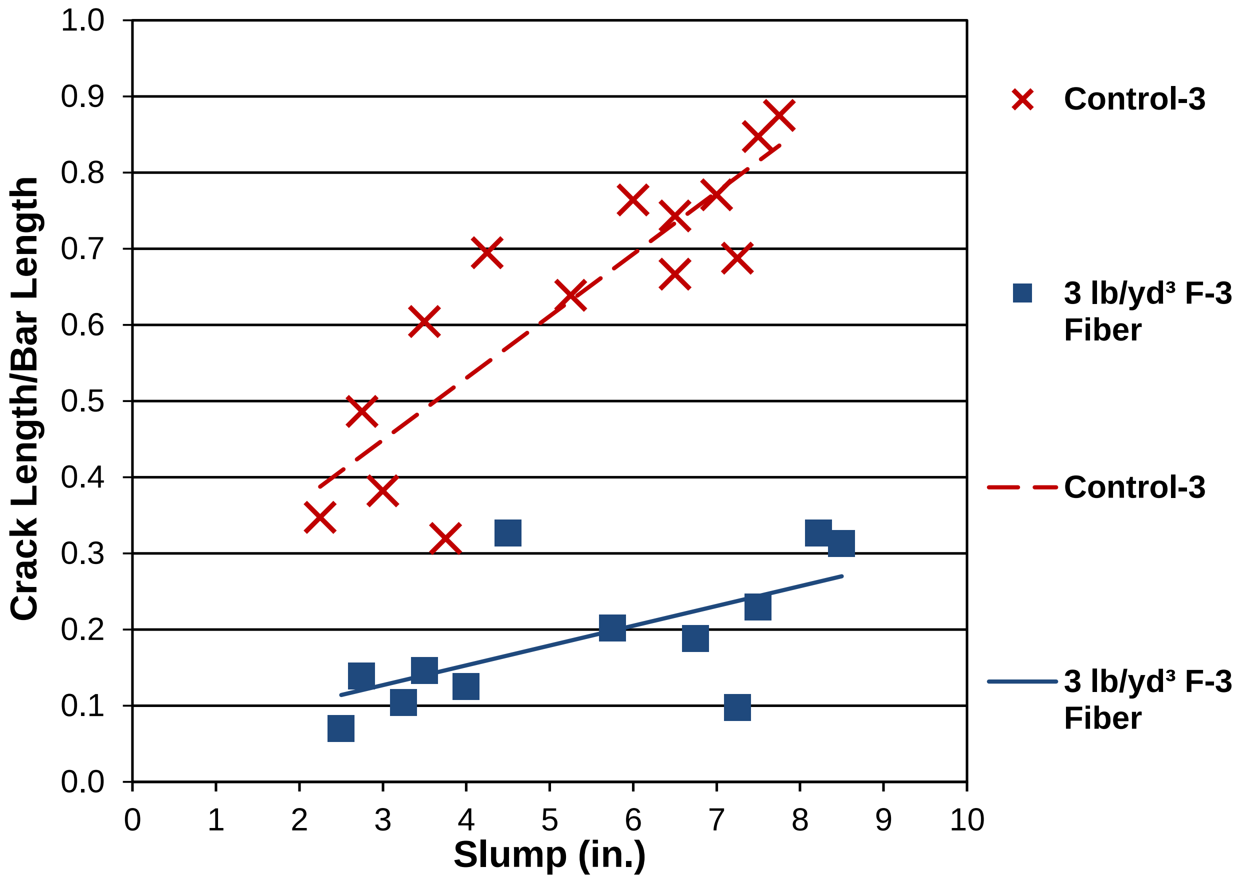


Figure 3.11: Settlement crack intensity versus slump for F-3 fiber and Control-3 mixtures.

3.4.5 F-4 Fiber

Two dosages of F-4 fiber were tested to examine the influence of fiber dosage on settlement cracking performance. The first series used a dosage of 1.5 lb/yd^3 (0.89 kg/m^3), while the second series used a dosage of 3 lb/yd^3 (1.78 kg/m^3).

3.4.5.1 Mixtures Containing 1.5 lb/yd^3 (0.89 kg/m^3) of F-4 fiber

Figure 3.12 shows settlement crack intensity versus slump for mixtures containing F-4 fiber. Twelve mixtures containing 1.5 lb/yd^3 (0.89 kg/m^3) of F-4 fiber were tested. The slump ranged from 2.75 to 8.25 in. (70 to 210 mm) and the crack intensity ranging from 0.08 to 0.28. Average crack intensity increased from 0.14 at a slump of 3 in. to 0.21 at a slump of 8 in. The average reduction in slump after adding 1.5 lb/yd^3 (0.89 kg/m^3) of F-4 fiber was 1.5 in. (40 mm). The slump values presented here are those obtained after adding F-4 fiber; slump values before the addition of F-4 fiber are presented in Appendix B.

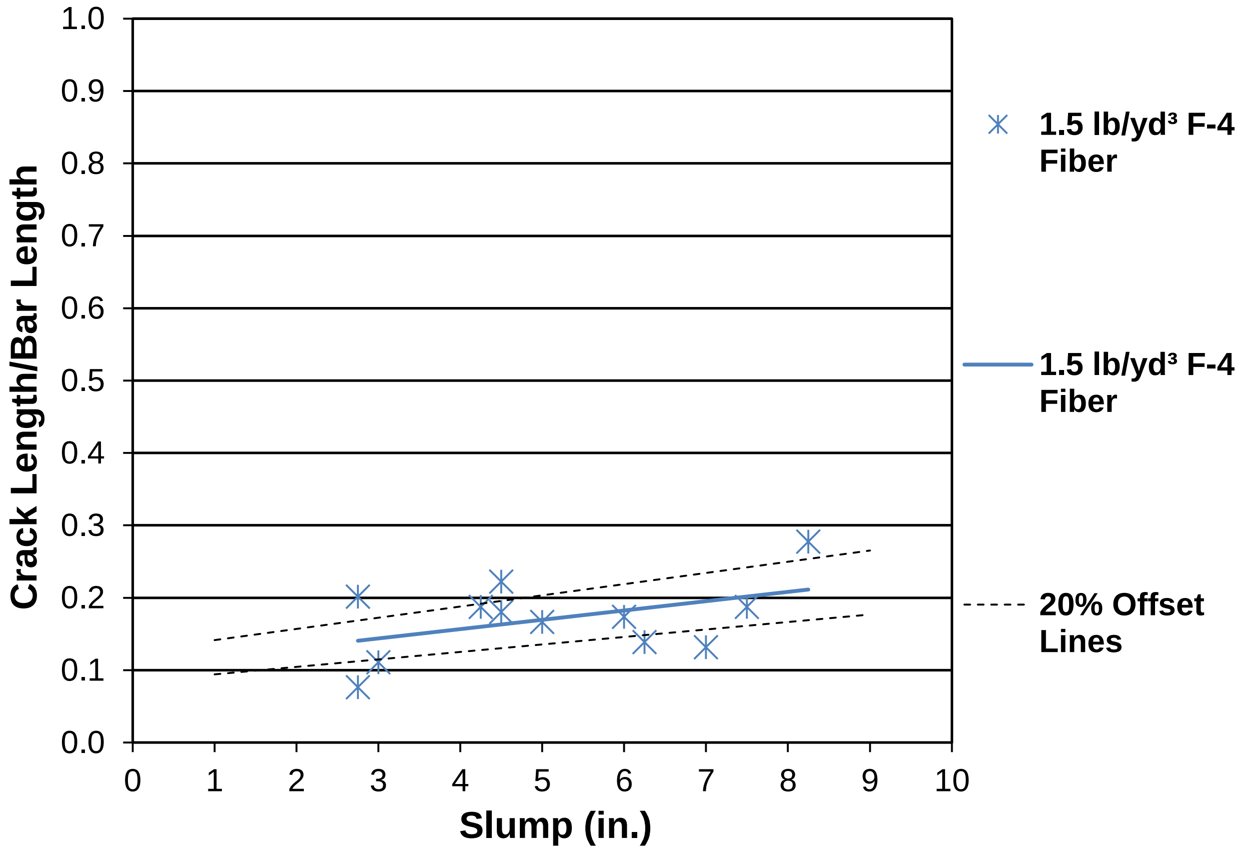


Figure 3.12: Settlement crack intensity versus slump for mixtures containing 1.5 lb/yd^3 (0.89 kg/m^3) of F-4 fiber.

Figure 3.13 shows settlement crack intensity for both the 1.5 lb/yd^3 (0.89 kg/m^3) F-4 fiber and Control-3 mixtures. Results show that the addition of this dosage of F-4 fiber reduced settlement cracking relative to control mixtures. No overlap in the data between the two series was observed. The improved cracking performance of F-4 fiber mixtures is consistent with that observed for the other mixtures containing fibers. The average reduction in the crack intensity between the Control-3 and F-4 fiber was 0.37 for a 4-in. (100-mm) slump mixture. Student's t-test shows these differences are statistically significant (α ranged from 2.57×10^{-6} to 4.19×10^{-18} over the slump range of 1 to 8 in. [25 to 205 mm]).

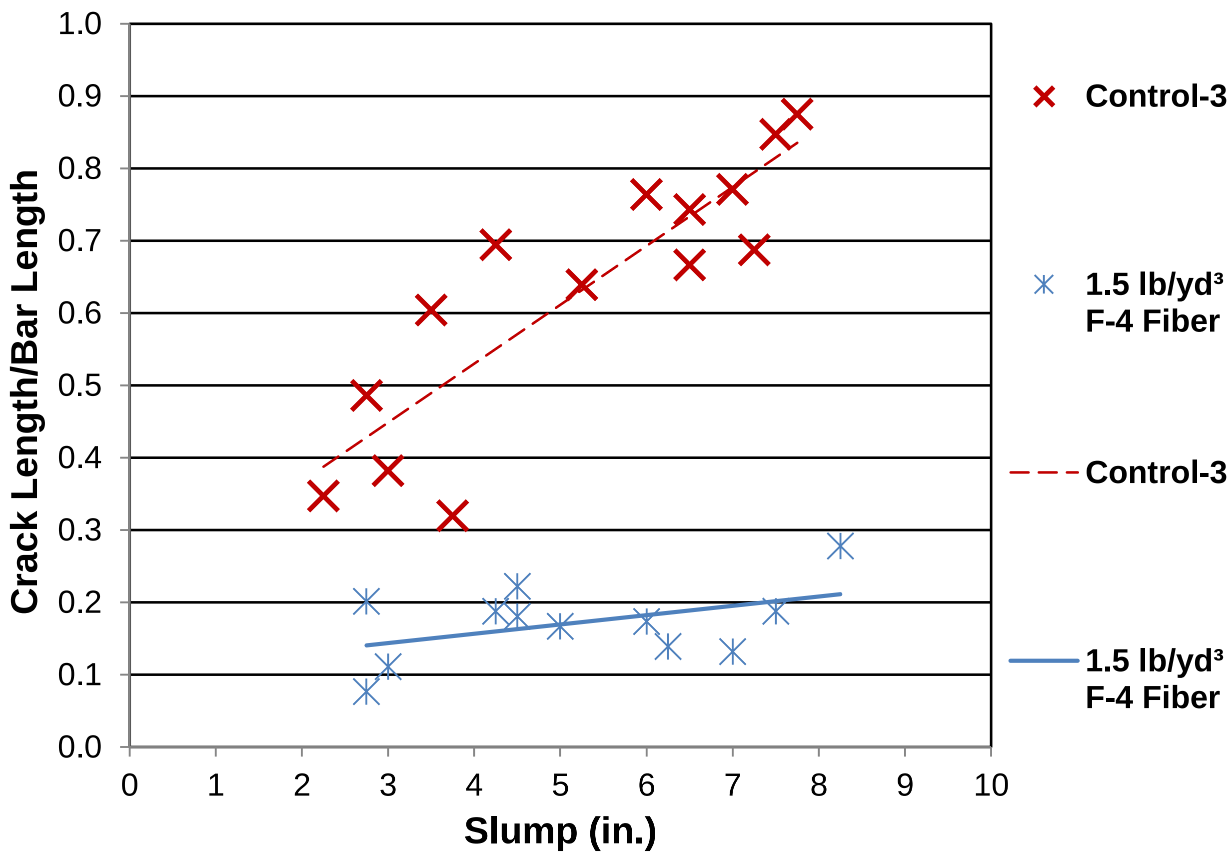


Figure 3.13: Settlement crack intensity versus slump for 1.5 lb/yd³ (0.89 kg/m³) F-4 fiber and Control-3 mixtures.

3.4.5.2 Mixtures Containing 3 lb/yd³ (1.78 kg/m³) of F-4 Fiber

Figure 3.14 shows settlement crack intensity versus slump for mixtures containing 3 lb/yd³ (1.78 kg/m³) of F-4 fiber. Eleven mixtures were tested. The slump ranged from 2.5 to 8.5 in. (65 to 215 mm), and the crack intensity ranged from 0.063 to 0.28. Average crack intensity increased from 0.13 at a slump of 3 in. to 0.23 at a slump of 8 in. The average reduction in slump after adding 3 lb/yd^3 (1.78 kg/m^3) of F-4 fiber was 2.0 in. (50 mm). The slump values presented here are those obtained after adding F-4 fiber; slump values before the addition of F-4 fiber are presented in Appendix B.

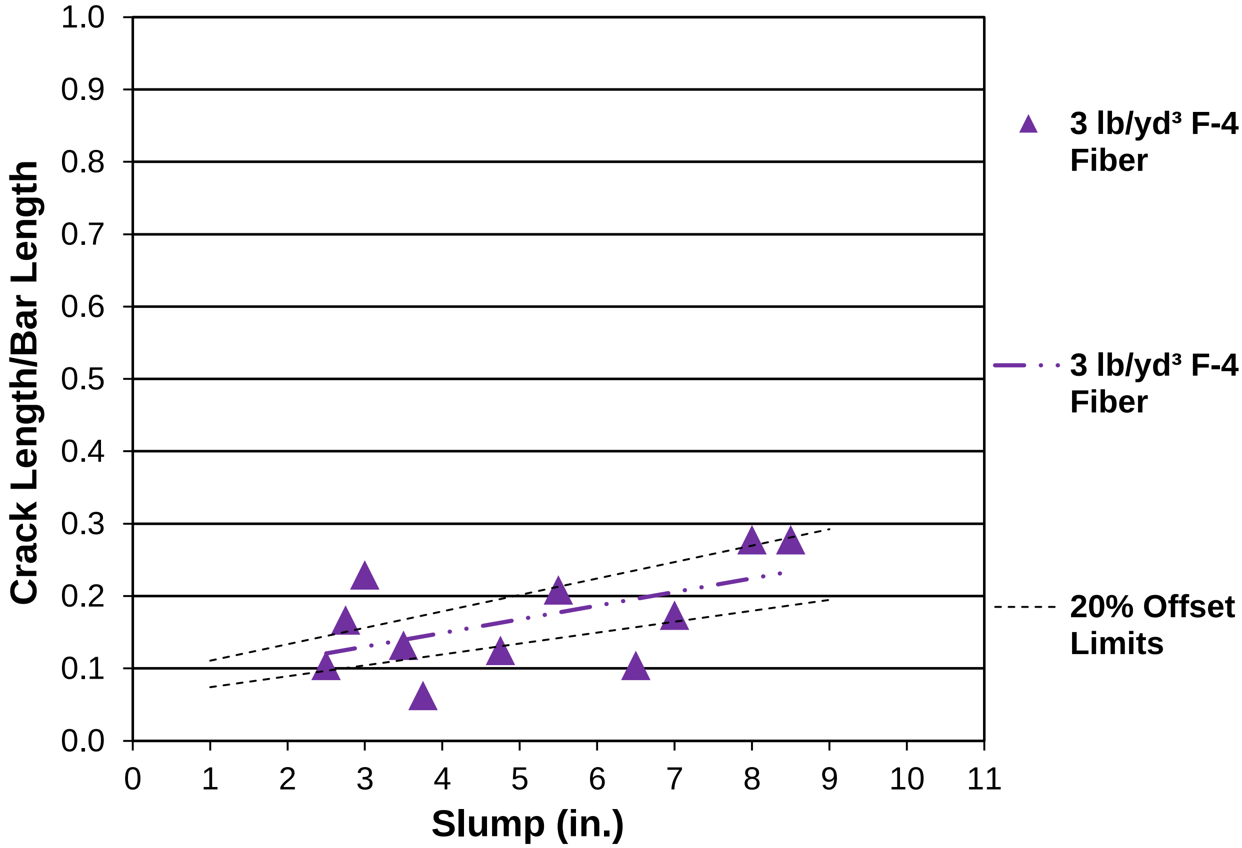


Figure 3.14: Settlement crack intensity versus slump for 3.0 lb/yd^3 (1.78 kg/yd^3) F-4 fiber mixtures.

Figure 3.15 shows settlement crack intensity for the 3.0 lb/yd^3 (1.78 kg/m^3) F-4 fiber and Control-3 mixtures. The results show that the addition of this dosage of F-4 fiber reduced settlement cracking relative to control mixtures. No overlap in the data between the two series was observed. The average reduction in the crack intensity between the Control-3 and F-4 fiber was

0.38 for 4 in. (100 mm) slump mixtures. Student's t-test shows these differences are statistically significant (α ranged from 1.31×10^{-6} to 1.47×10^{-16} over the slump range of 1 to 8 in. [25 to 205 mm]).

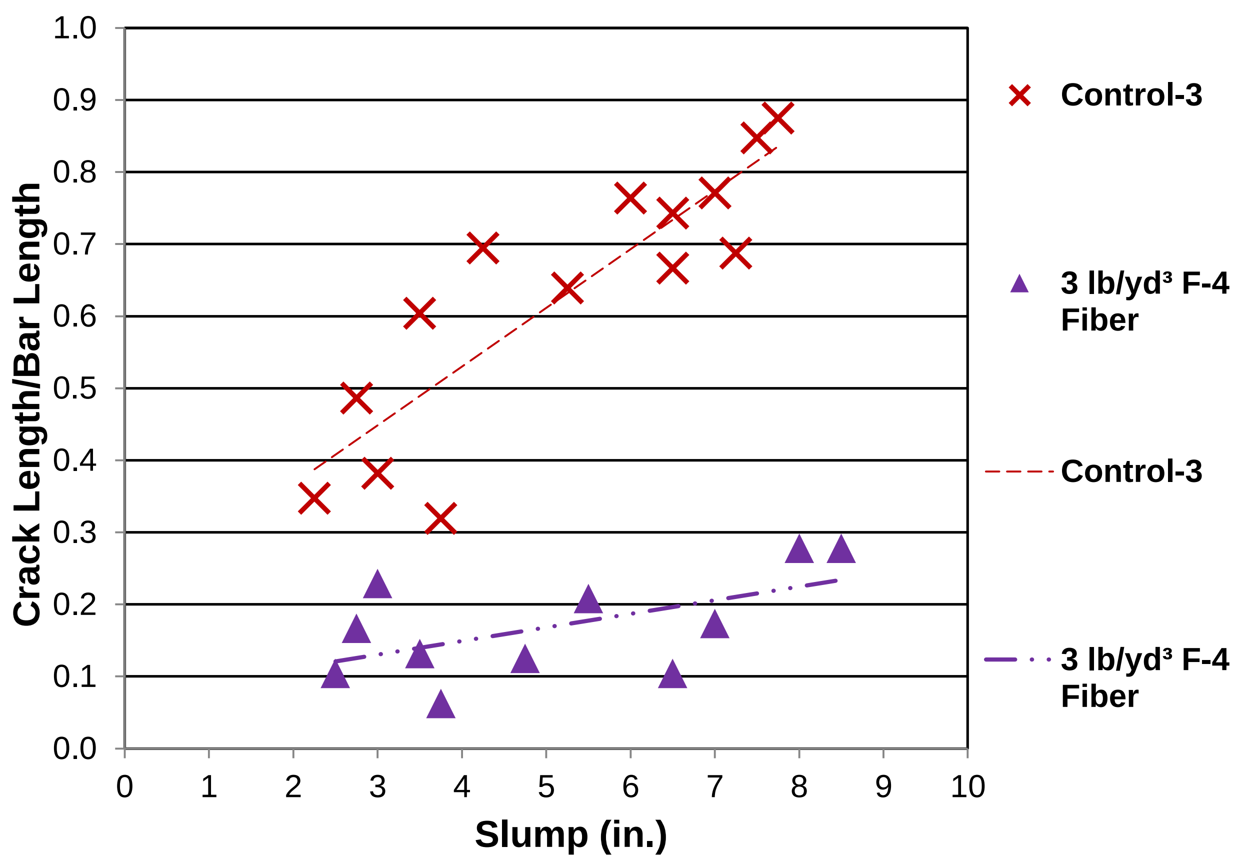


Figure 3.15: Settlement crack intensity versus slump for 3.0 lb/yd^3 (1.78 kg/yd^3) F-4 fiber and Control-3 mixtures.

Figure 3.16 shows settlement crack intensity for both the 3.0 lb/yd^3 (1.78 kg/m^3) and the 1.5 lb/yd^3 (0.89 kg/m^3) F-4 fiber mixtures. No significant difference in the cracking performance was observed between the two dosages of F-4 fiber. The manufacturer's recommended dosage of 1.5 lb/yd^3 (0.89 kg/m^3) seems to provide enough fibers in the concrete matrix to reduce settlement cracking. Student's t-test confirms these differences are not statistically significant (α ranged from 0.2525 to 0.4549 over the slump range of 1 to 8 in. [25 to 205 mm]).

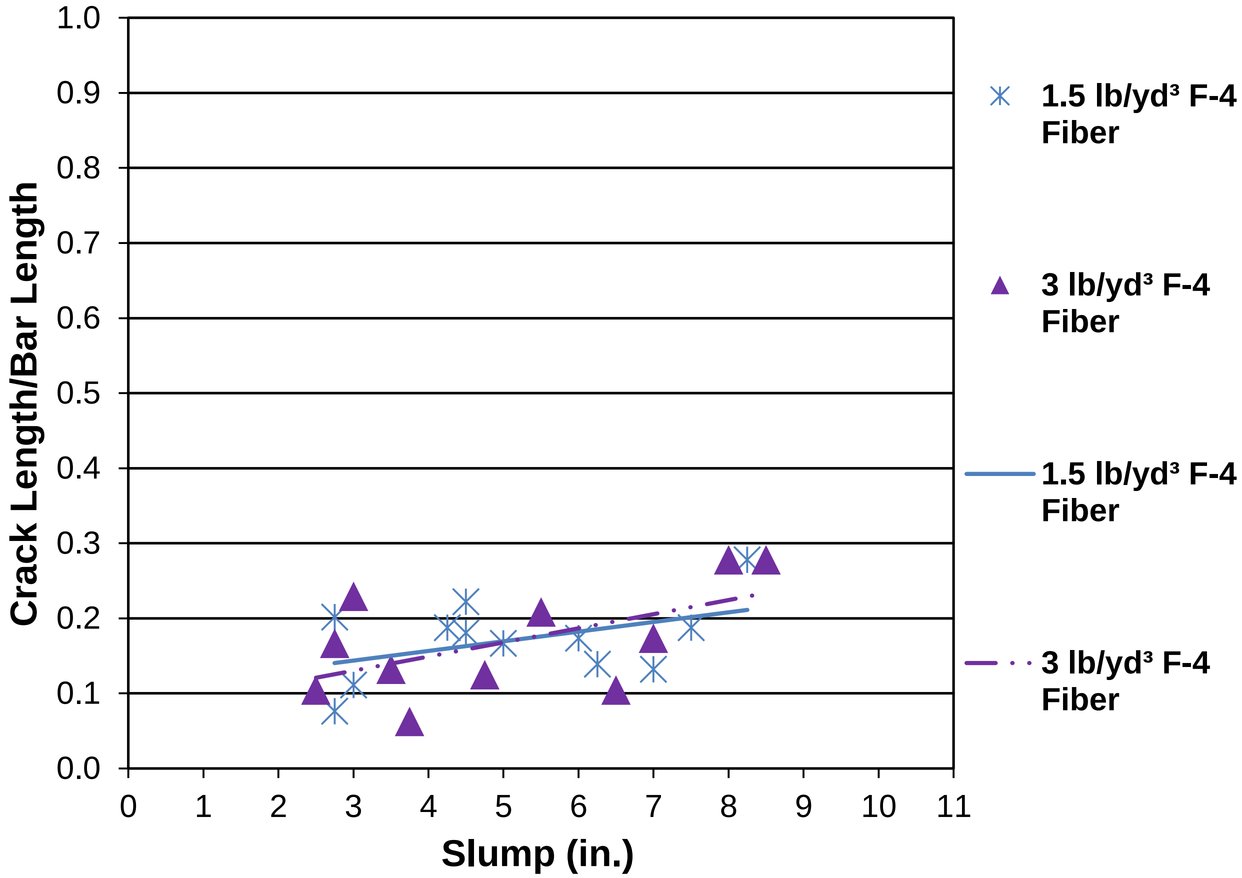


Figure 3.16: Settlement crack intensity versus slump for 1.5 lb/yd^3 (0.89 kg/m^3) and 3.0 lb/yd^3 (1.78 kg/yd^3) F-4 fiber mixtures.

3.4.6 VMA-1

Figure 3.17 shows settlement crack intensity versus slump for the mixtures containing VMA-1. Seventeen mixtures containing VMA-1 dosed at 0.05% of total mixture dry weight were tested. The slump ranged from 1.75 to 7.75 in. (45 to 195 mm) and the crack intensity ranged from 0.22 to 0.64. Average crack intensity increased from 0.29 at a slump of 3 in. to 0.55 at a slump of 8 in. Fresh concrete slump was measured before and after adding the VMA-1 to determine its influence on the slump. The average reduction in slump after adding the VMA-1 was 2.0 in. (50 mm). The slump values presented here are those obtained after adding VMA-1; slump values before the addition of VMA-1 are presented in Appendix B.

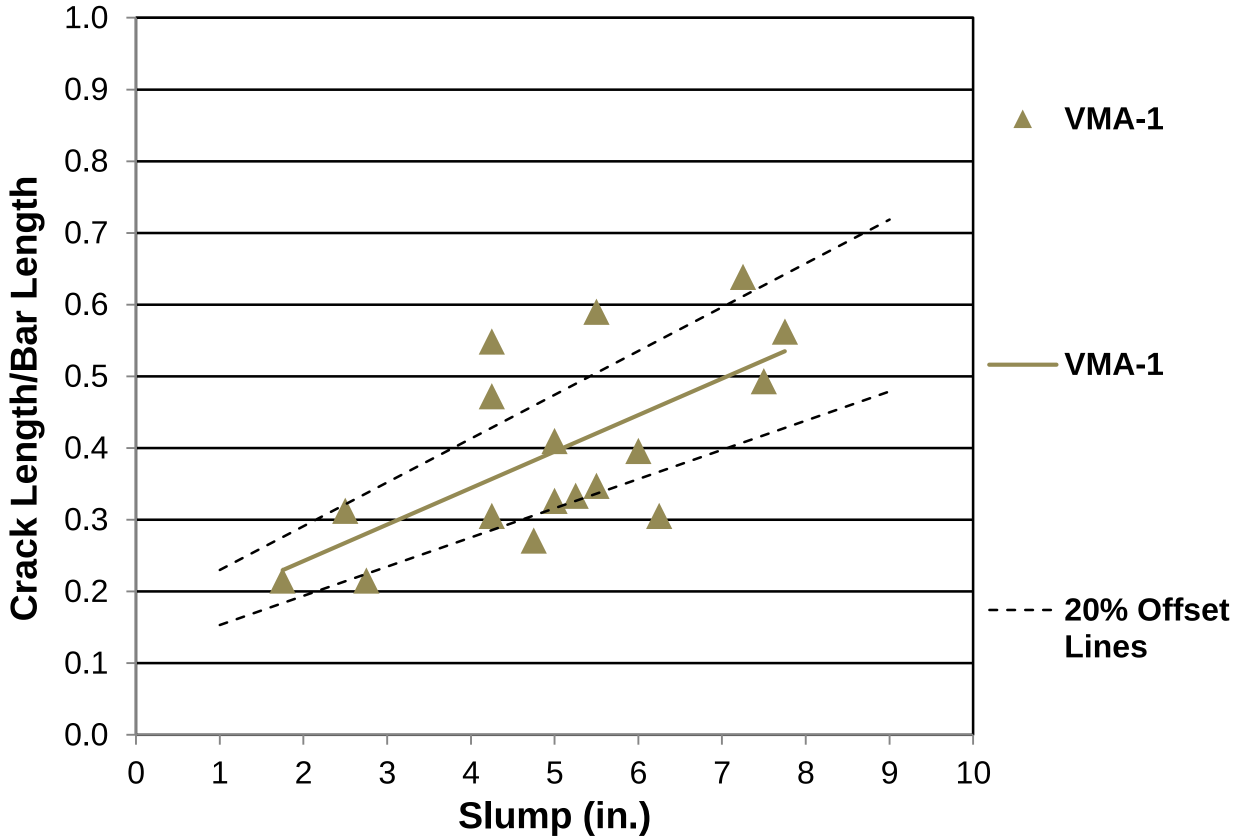


Figure 3.17: Settlement crack intensity versus slump for VMA-1 mixtures.

Figure 3.18 shows settlement crack intensity for the Control-3 and VMA-1 mixtures. The addition of VMA-1 reduced cracking compared to control mixtures, with relatively better cracking performance for low slump than higher slump mixtures. The average reduction in the crack intensity between the Control-3 and VMA-1 was 0.19 for a 4-in. (100-mm) slump. Student's t-test shows these differences are statistically significant (α ranged from 0.00756 to 2.81×10^{-10} over the slump range of 1 to 8 in. [25 to 205 mm]). VMA-1 tended to increase the cohesiveness of the plastic concrete and the stability of the concrete matrix, which resulted in less settlement around the reinforcing bar and led to an improvement in the settlement cracking performance.

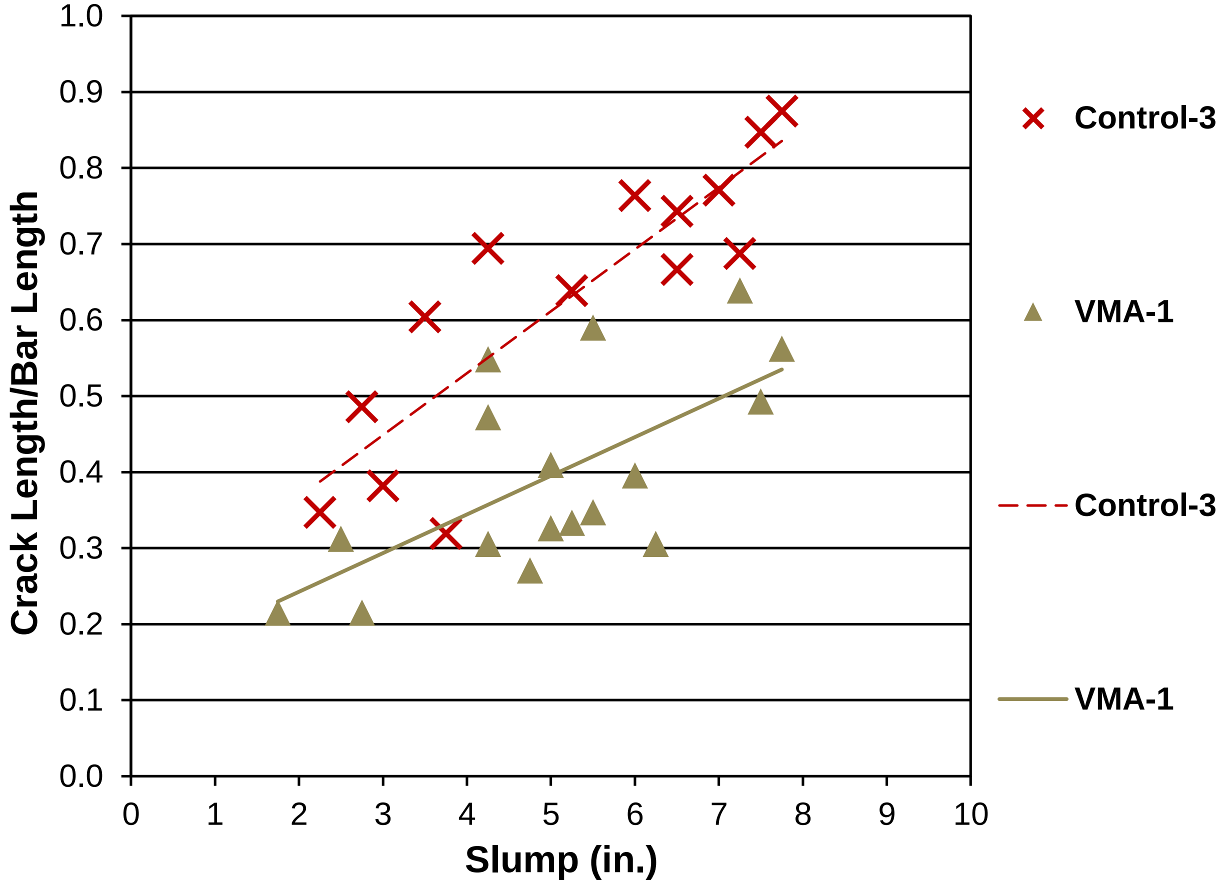


Figure 3.18: Settlement crack intensity versus slump for VMA-1 and Control-3 mixtures.

3.5 Effect of Fiber Type and Comparison to Earlier Research

Figure 3.19 shows settlement crack intensity versus slump for all mixtures in this study containing fibers. As shown in the figure, the effect of fibers on settlement cracking is similar for the fibers studied. Student's t-test indicates that the observed differences in settlement cracking are not significant with the exception between F-2 fiber at 7.5 lb/yd^3 and F-1 fiber at 3 lb/yd^3 (α ranged from 0.005 to 0.0294 over the slump range of 1 in. to 8 in. [25 to 205 mm]).In contrast to the observations of Suprenant and Malisch (1999) that indicated that the use of 1.25 lb/yd^3 (0.74 kg/m^3) of fibrillated polypropylene fibers totally eliminated settlement cracking, the fibers in this study reduced but did not eliminate settlement cracking. The apparent superior performance exhibited in the study by Suprenant and Malisch is likely the result of the fact that they used concrete from a single ready-mix truck to which the fibers were added only after all of the control specimens had been cast. The resulting 40-minute delay presumably lead faster setting relative to that of the concrete without fibers.

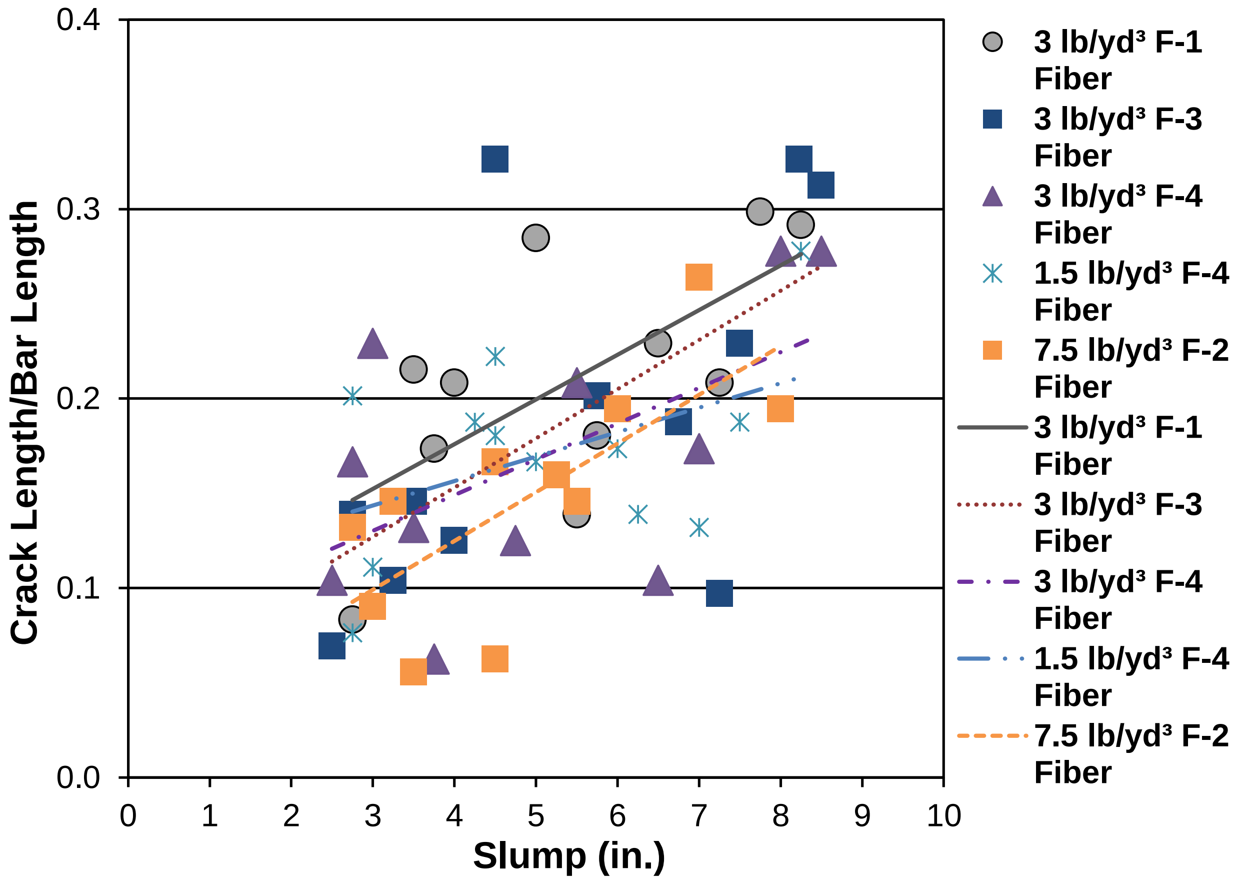


Figure 3.19: Settlement crack intensity versus slump for all series of fibers examined.

3.6 Comparison between Mixtures containing Fibers and VMA-1

Figure 3.20 compares settlement cracking performance of mixtures containing fibers and those containing VMA-1. As shown in the figure, mixtures containing fibers exhibited less settlement cracking than the mixtures containing VMA-1. Student's t-test confirms the difference in performance between mixtures is statistically significant. It is worth noting, however, that for a given slump, concrete containing VMA-1 is more workable than concrete containing fibers when a shear force is applied, such as when mixing, pumping, or consolidating the concrete, and both fibers and VMA-1 significantly reduce settlement cracking compared to the control mixtures.

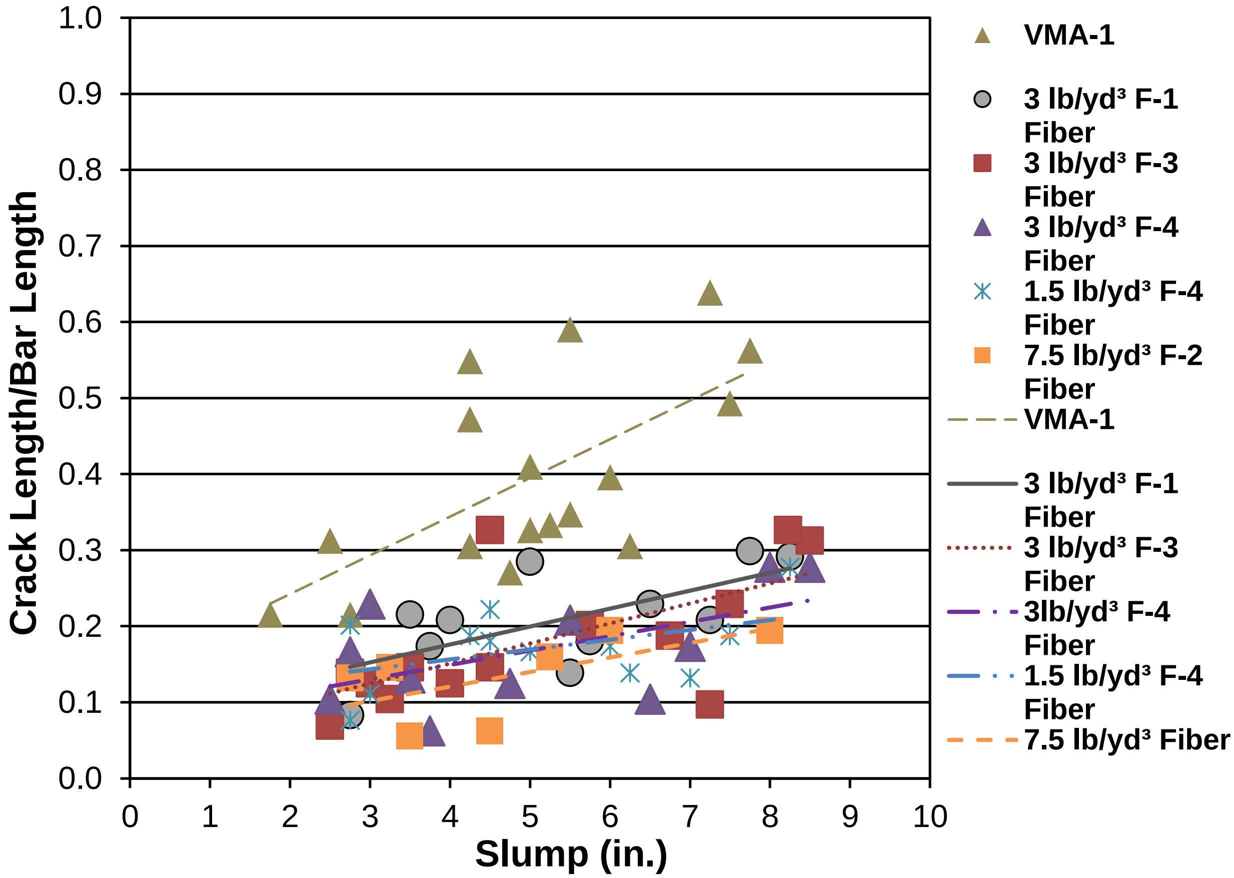


Figure 3.20: Settlement crack intensity for all mixtures containing fibers compared to VMA-1.

3.7 Summary

The effect of synthetic fibers and a rheology modifier on the settlement crack behavior of concrete mixtures were investigated in this study. The results show that the addition of the fibers and the rheology modifier significantly reduced the settlement cracking compared to a series of control mixtures that did not contain a crack reduction technology (labeled as Control-3 series).

Chapter 4 SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

4.1 Summary

Settlement cracking is a significant source of cracking in bridge decks. The presence of cracks in bridge decks provides a site for continued crack growth due to other causes, accelerates freeze-thaw damage, and exposes the reinforcement to corrosive salts. Many transportation agencies have acknowledged cracks as a serious problem that affects the durability of bridge decks.

Three series of concrete mixtures, consisting of 133 batches, were tested. The first series consisted of 27 control mixtures with a 24.3 percent cement paste content by volume and a water-to-cement ratio of 0.5. The second series consisted of 18 control mixtures with a 27 percent cement paste content by volume and a water-to-cement ratio of 0.45. The third series consisted of 88 mixtures with a 27 percent cement paste content and a water-to-cement ratio of 0.45. Fourteen mixtures in this series served as controls; the remaining 74 mixtures were used to evaluate the effectiveness of crack reduction technologies on settlement cracking performance; 57 mixtures contained from 1.5 lb/yd^3 (0.89 kg/m^3) to 7.5 lb/yd^3 (4.45 kg/m^3) of one of four different synthetic fibers, and 17 mixtures contained a rheology modifier in the form of a dry viscosity modifying admixture (dosed at 0.05% of mixture material dry weight).

4.2 Conclusions

Based on the results of this study, the following conclusions can be drawn:

1) The settlement cracking for a given mixture increases as the slump increases.
2) Adding the viscosity modifying admixture to the concrete significantly reduces the amount of settlement cracking.

3) Adding the fibers at the dosage rates used in the study to concrete significantly reduces the amount of settlement cracking.
4) Doubling the recommended dosage of 1.5 lb/yd3 (0.89 kg/m3) of one fiber had no significant effect on the settlement cracking performance. The manufacturer's recommended dosage was sufficient to significantly reduce settlement cracking.
5) With one exception, no statistically significant difference in settlement cracking was observed between different types of fibers.
6) Mixtures containing the viscosity modifying admixture exhibit more settlement cracking than mixtures containing any of the fibers tested. However, for a given slump, concrete containing the viscosity modifying admixture is more workable when shear force is applied compared to concrete containing fibers.

4.3 Recommendations

In this study, the effects of synthetic fibers and a rheology modifier were tested to evaluate their influence on reducing settlement cracking; however, the addition of supplementary cementitious materials, such as silica fume or slag, was not tested. Since supplementary cementitious materials can reduce the bleed water in plastic concrete, further research is recommended to determine the effect of the addition of supplementary cementitious materials on settlement cracking performance of concrete mixtures containing fibers and rheology modifiers.

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APPENDIX A

SIEVE ANALYSIS OF AGGREGATE

Table A.1: Sieve Analysis of Fine Aggregate (Sand).

Sieve Number	Sieve Weight	Sieve + F.A. Weight	Weight of F.A. Retained	% Weight of F.A. Retained	Cumulative % Retained	% Passing
No. 4	750.3	760.3	10	1.82%	1.82%	98.18%
No. 8	475.4	549.4	74	13.50%	15.33%	84.67%
No. 16	446.1	572.7	126.6	23.10%	38.43%	61.57%
No. 30	386.2	513.3	127.1	23.19%	61.62%	38.38%
No. 50	382.5	495.2	112.7	20.57%	82.19%	17.81%
No. 100	328.8	398.9	70.1	12.79%	94.98%	5.02%
No. 200	322.4	341	18.6	3.39%	98.38%	1.62%
Pan	362.5	371.4	8.9	1.62%	100.00%	0.00%
Sum			548	100.00%		

Table A.2: Sieve Analysis of Fine Aggregate (Pea Gravel).

Sieve Number	Sieve Weight	Sieve + F.A. Weight	Weight of F.A. Retained	% Weight of F.A. Retained	Cumulative % Retained	% Passing
No. 4	750.8	853.3	102.5	11.25%	11.25%	88.75%
No. 8	475.9	1072.8	596.9	65.54%	76.79%	23.21%
No. 16	446.2	613.9	167.7	18.41%	95.20%	4.80%
No. 30	386.4	408.2	21.8	2.39%	97.60%	2.40%
No. 50	382.4	391.6	9.2	1.01%	98.61%	1.39%
No. 100	329.1	333.3	4.2	0.46%	99.07%	0.93%
No. 200	322.4	325.4	3	0.33%	99.40%	0.60%
Pan	362.5	368	5.5	0.60%	100.00%	0.00%
Sum	----	----	910.8	100.00%	----	----

Table A.3: Sieve Analysis of Coarse Aggregate (Granite A).

Sieve Number	Sieve Weight	Sieve + C.A. Weight	Weight of C.A. Retained	% Weight of C.A. Retained	Cumulative % Retained	% Passing
1 ½ in.	21.14	21.14	0	0.00%	0.00%	100.00%
1 in.	18.2	18.42	0.22	1.60%	1.60%	98.40%
¾ in.	21.32	24.51	3.19	23.25%	24.85%	75.15%
½ in.	22.23	32.21	9.98	72.74%	97.59%	2.41%
⅜ in.	22.47	22.76	0.29	2.11%	99.71%	0.29%
No. 4	18.95	18.95	0	0.00%	99.71%	0.29%
No. 8	17.9	17.9	0	0.00%	99.71%	0.29%
Pan	18.48	18.52	0.04	0.29%	100.00%	0.00%
Sum	----	----	14.25	100.00%	----	----

Table A.4: Sieve Analysis of Coarse Aggregate (Granite B).

Sieve Number	Sieve Weight	Sieve + C.A. Weight	Weight of C.A. Retained	% Weight of C.A. Retained	Cumulative % Retained	% Passing
1 ½ in.	21.14	21.14	0	0.00%	0.00%	100.00%
1 in.	18.14	18.14	0	0.00%	0.00%	100.00%
¾ in.	20.85	21.54	0.69	4.84%	4.84%	95.16%
½ in.	19.18	31.84	12.66	88.84%	93.68%	6.32%
⅜ in.	22.18	22.9	0.72	5.05%	98.74%	1.26%
No. 4	19.36	19.36	0	0.00%	98.74%	1.26%
No. 8	18.45	18.45	0	0.00%	98.74%	1.26%
Pan	19.5	19.68	0.18	1.26%	100.00%	0.00%
Sum	----	----	14.25	100.00%	----	----

Table A.5: Sieve Analysis of Coarse Aggregate (Granite C).

Sieve Number	Sieve Weight	Sieve + C.A. Weight	Weight of C.A. Retained	% Weight of C.A. Retained	Cumulative % Retained	% Passing
1 ½ in.	21.14	21.14	0	0.00%	0.00%	100.00%
1 in.	18.14	18.14	0	0.00%	0.00%	100.00%
¾ in.	20.84	20.84	0	0.00%	0.00%	100.00%
½ in.	19.16	21.82	2.66	17.52%	17.52%	82.48%
⅜ in.	22.14	29.32	7.18	47.30%	64.82%	35.18%
No. 4	19.34	24.48	5.14	33.86%	98.68%	1.32%
No. 8	18.4	18.4	0	0.00%	98.68%	1.32%
Pan	19.68	19.88	0.2	1.32%	100.00%	0.00%
Sum	----	----	15.18	100.00%	----	----

APPENDIX B

TEMPERATURE, SLUMP BEFORE AND AFTER THE ADDITION OF THE CRACK REDUCTION TECHNOLOGIES, AND SETTLEMENT CRACKING RESULTS

Table B.1: Settlement cracking results of Control-1 series.

Batch No.	Slump, in.	Concrete Temperature, ° F	Specimen Number	Settlement Cracks	Crack Width	Crack Length, in.	Average Crack Intensity*
S90	1.25	63	1	yes	<2 mils	0.25	0.208
			2	yes	<2 mils	5.5	
			3	yes	<2 mils	1.75	
S91	8	62	1	yes	<2 mils	6.25	0.424
			2	yes	<2 mils	5	
			3	yes	<2 mils	4	
S92	7.5	66	1	yes	<2 mils	3.75	0.493
			2	yes	<2 mils	7.75	
			3	yes	<2 mils	6.25	
S94	8.25	61	1	yes	<2 mils	8.5	0.701
			2	yes	<2 mils	8.25	
			3	yes	<2 mils	8.5	
S95	9	63	1	yes	<2 mils	9.25	0.806
			2	yes	3 mils	9.5	
			3	yes	3 mils	10.25	
S96	7.25	60	1	yes	<2 mils	7	0.611
			2	yes	<2 mils	7.25	
			3	yes	<2 mils	7.75	
S97	4.5	60	1	yes	<2 mils	9	0.729
			2	yes	<2 mils	8	
			3	yes	<2 mils	9.25	
S98	2.75	70	1	yes	2 mils	7.25	0.361
			2	yes	<2 mils	2	
			3	yes	<2 mils	3.75	
S99	8.25	68	1	yes	<2 mils	6.5	0.493
			2	yes	<2 mils	3.5	
			3	yes	3 mils	7.75	
S100	7.25	70	1	yes	5 mils	11.25	0.875
			2	yes	5 mils	10.5	
			3	yes	5 mils	9.75	
S101	1.25	68	1	yes	2 mils	10.25	0.785
			2	yes	2 mils	9	
			3	yes	2 mils	9	

* The total length of cracks found on the specimen surface divided by the length of the reinforcing bar (12 in. [305 mm]), values presented for each mixture are the average of three specimens (applies to all tables).

Table B.1 (Continued): Settlement cracking results of Control-1 series.

Batch No.	Slump, in.	Concrete Temperature, ° F	Specimen Number	Settlement Cracks	Crack Width	Crack Length, in.	Average Crack Intensity
S109	1.25	70	1	yes	<2 mils	1	0.181
			2	yes	<2 mils	5	
			3	yes	<2 mils	0.5	
S110	4.25	66	1	yes	2 mils	6.75	0.625
			2	yes	<2 mils	6.5	
			3	yes	<2 mils	9.25	
S111	4.5	66	1	yes	<2 mils	3	0.319
			2	yes	<2 mils	3	
			3	yes	2 mils	5.5	
S112	1.25	67	1	yes	<2 mils	3.75	0.229
			2	yes	<2 mils	1	
			3	yes	<2 mils	3.5	
S113	6.75	65	1	yes	<2 mils	5.25	0.458
			2	yes	<2 mils	5.75	
			3	yes	<2 mils	5.5	
S114	5	69	1	yes	<2 mils	3.75	0.639
			2	yes	<2 mils	8.5	
			3	yes	<2 mils	10.75	
S115	4	65	1	yes	<2 mils	6.25	0.417
			2	yes	<2 mils	4	
			3	yes	3 mils	4.75	
S116	4.5	65	1	yes	<2 mils	0.5	0.076
			2	no	0 mils	0	
			3	yes	2 mils	2.25	
S117	2.75	65	1	yes	3 mils	2	0.132
			2	yes	<2 mils	1.75	
			3	yes	<2 mils	1	
S118	3.25	65	1	yes	<2 mils	3	0.264
			2	yes	<2 mils	4	
			3	yes	<2 mils	2.5	
S129	6.25	62	1	yes	2 mils	7.5	0.521
			2	yes	2 mils	7	
			3	yes	<2 mils	4.25	
S133	4.5	68	1	yes	2 mils	7.75	0.646
			2	yes	3 mils	11	
			3	yes	< 2 mils	4.5	

Table B.1 (Continued): Settlement cracking results of Control-1 series.

Batch No.	Slump, in.	Concrete Temperature, ° F	Specimen Number	Settlement Cracks	Crack Width	Crack Length, in.	Average Crack Intensity
136	8	68	1	yes	2 mils	9.25	0.667
			2	yes	2 mils	8.5	
			3	yes	2 mils	6.25	
S159	7.5	65	1	Yes	< 2 mils	5.25	0.333
			2	Yes	< 2 mils	2	
			3	Yes	< 2 mils	4.75	
S160	7.75	67	1	Yes	< 2 mils	4.75	0.556
			2	Yes	2 mils	8.25	
			3	Yes	3 mils	7	
S162	4.5	68	1	Yes	<2 mils	4.75	0.507
			2	Yes	<2 mils	4.5	
			3	Yes	2 mils	9	

Table B.2: Settlement cracking results of Control-2 series.

Batch No.	Slump, in.	Concrete Temperature, ° F	Specimen Number	Settlement Cracks	Crack Width	Crack Length, in.	Average Crack Intensity
S163	6.25	68	1	Yes	2 mils	8.5	0.694
			2	Yes	2 mils	10	
			3	Yes	3 mils	6.5	
S164	4	66	1	Yes	2 mils	8.75	0.785
			2	Yes	4 mils	9.5	
			3	Yes	2 mils	10	
S165	4	64	1	Yes	4 mils	8.25	0.729
			2	Yes	3 mils	8.75	
			3	Yes	12 mils	9.25	
S166	1.75	63	1	Yes	< 2 mils	1.75	0.41
			2	Yes	3 mils	6.25	
			3	Yes	4 mils	6.75	
S167	3.5	62	1	Yes	6 mils	9.5	0.444
			2	Yes	< 2 mils	4	
			3	Yes	< 2 mils	2.5	
S168	3	61	1	Yes	4 mils	4.75	0.375
			2	Yes	4 mils	5.75	
			3	Yes	2 mils	3	
S169	6.5	63	1	Yes	< 2 mils	9.25	0.535
			2	Yes	< 2 mils	4.5	
			3	Yes	< 2 mils	5.5	
S170	7.25	62	1	Yes	2 mils	9	0.563
			2	Yes	3 mils	9.5	
			3	Yes	< 2 mils	1.75	
S171	8	66	1	Yes	< 2 mils	10.5	0.757
			2	Yes	< 2 mils	10.25	
			3	Yes	< 2 mils	6.5	
S172	2.5	65	1	Yes	2 mils	7	0.528
			2	Yes	< 2 mils	5.75	
			3	Yes	2 mils	6.25	
S173	5.5	69	1	Yes	< 2 mils	8.75	0.66
			2	Yes	< 2 mils	8.5	
			3	Yes	2 mils	6.5	
S174	5	68	1	Yes	2 mils	3.5	0.486
			2	Yes	< 2 mils	7	
			3	Yes	2 mils	7	

Table B.2 (Continued): Settlement cracking results of Control-2 series.

Batch No.	Slump, in.	Concrete Temperature, ° F	Specimen Number	Settlement Cracks	Crack Width	Crack Length, in.	Average Cracking Intensity
S175	7	69	1	Yes	< 2 mils	7.75	0.75
			2	Yes	< 2 mils	10	
			3	Yes	< 2 mils	9.25	
S176	8.25	69	1	Yes	2 mils	9.25	0.771
			2	Yes	< 2 mils	10.75	
			3	Yes	< 2 mils	7.75	
S177	3.25	69	1	Yes	< 2 mils	7.25	0.722
			2	Yes	< 2 mils	9.75	
			3	Yes	< 2 mils	9	
S178	3	69	1	Yes	2 mils	7.5	0.611
			2	Yes	3 mils	7.25	
			3	Yes	2 mils	7.25	
S179	3	68	1	Yes	< 2 mils	5.25	0.403
			2	Yes	< 2 mils	4.75	
			3	Yes	< 2 mils	4.5	
S260	6.75	71	1	Yes	2 mils	9	0.59
			2	Yes	< 2 mils	4	
			3	Yes	2 mils	8.25	

Table B.3: Settlement cracking results of Control-3 series.

Mixture No.	Slump, in.	Concrete Temperature, ° F	Specimen Number	Settlement Cracks	Crack Width	Crack Length, in.	Crack Length/Bar Length
S284	3	71	1	Yes	3 mils	6.5	0.382
			2	Yes	< 2 mils	2.75	
			3	Yes	< 2 mils	4.5	
S285	2.25	71	1	Yes	2 mils	5.5	0.347
			2	Yes	2 mils	2.5	
			3	Yes	3 mils	4.5	
S286	6	72	1	Yes	2 mils	10.5	0.764
			2	Yes	< 2 mils	6.75	
			3	Yes	3 mils	10.25	
S287	5.25	72	1	Yes	2 mils	11.5	0.639
			2	Yes	2 mils	6.75	
			3	Yes	3 mils	4.75	
S288	2.75	73	1	Yes	3 mils	3.75	0.486
			2	Yes	< 2 mils	5.25	
			3	Yes	2 mils	8.5	
S289	3.5	72	1	Yes	2 mils	8	0.604
			2	Yes	< 2 mils	5.75	
			3	Yes	< 2 mils	8	
S291	7.75	73	1	Yes	< 2 mils	10.5	0.875
			2	Yes	< 2 mils	9.75	
			3	Yes	2 mils	11.25	
S292	7.25	72	1	Yes	2 mils	7	0.688
			2	Yes	2 mils	7.75	
			3	Yes	3 mils	10	
S293	6.5	73	1	Yes	2 mils	8.5	0.743
			2	Yes	2 mils	8.75	
			3	Yes	2 mils	9.5	
S295	3.75	71	1	Yes	< 2 mils	2.75	0.319
			2	Yes	2 mils	5.5	
			3	Yes	2 mils	3.25	
S297	6.5	74	1	Yes	< 2 mils	9	0.667
			2	Yes	< 2 mils	3.75	
			3	Yes	2 mils	11.25	
S298	7	74	1	Yes	2 mils	10.25	0.771
			2	Yes	2 mils	7.5	
			3	Yes	3 mils	10	

Table B.3 (Continued): Settlement cracking results of Control-3 series.

Mixture No.	Slump, in.	Concrete Temperature, ° F	Specimen Number	Settlement Cracks	Crack Width	Crack Length, in.	Crack Length/Bar Length
S299	4.25	75	1	Yes	2 mils	8	0.694
			2	Yes	2 mils	8.5	
			3	Yes	2 mils	8.5	
S300	7.5	73	1	Yes	2 mils	8.5	0.847
			2	Yes	2 mils	10.5	
			3	Yes	3 mils	11.5	

Table B.4: Settlement cracking results of F-1 fiber series.

Batch No.	Initial Slump*, in.	Final Slump**, in.	Concrete Temperature, ° F	Specimen Number	Settlement Cracks	Crack Width	Crack Length, in.	Average Cracking Intensity
S259	8	5	74	1	Yes	2 mils	6	0.285
				2	Yes	2 mils	3.25	
				3	Yes	< 2 mils	1	
S261	6.25	4	73	1	Yes	< 2 mils	1.5	0.208
				2	Yes	5 mils	4	
				3	Yes	2 mils	2	
S262	5	2.75	74	1	Yes	< 2 mils	0.75	0.083
				2	Yes	< 2 mils	0.25	
				3	Yes	< 2 mils	2	
S264	8.25	5.75	73	1	Yes	< 2 mils	3.75	0.181
				2	Yes	2 mils	1	
				3	Yes	< 2 mils	1.75	
S265	9.5	7.75	74	1	Yes	2 mils	4.5	0.299
				2	Yes	2 mils	3.75	
				3	Yes	< 2 mils	2.5	
S266	10	8.25	74	1	Yes	< 2 mils	4	0.292
				2	Yes	2 mils	5	
				3	Yes	< 2 mils	1.5	
S268	8	5.5	74	1	Yes	< 2 mils	2.75	0.139
				2	Yes	< 2 mils	1.25	
				3	Yes	< 2 mils	1	
S269	8.75	6.5	73	1	Yes	< 2 mils	4	0.229
				2	Yes	2 mils	2.5	
				3	Yes	< 2 mils	1.75	
S270	8.25	7.25	74	1	Yes	< 2 mils	1.5	0.208
				2	Yes	< 2 mils	1.5	
				3	Yes	< 2 mils	4.5	
S271	6.25	3.5	74	1	Yes	2 mils	2.25	0.215
				2	Yes	2 mils	3.25	
				3	Yes	< 2 mils	2.25	
S272	5.25	3.75	74	1	Yes	< 2 mils	2	0.174
				2	Yes	< 2 mils	1.5	
				3	Yes	< 2 mils	2.75	

* Slump before the addition of the crack reduction technology.
** Slump after the addition of the crack reduction technology.

Table B.5: Settlement cracking results of F-2 fiber series.

Batch No.	Initial Slump*, in.	Final Slump**, in.	Concrete Temperature, ° F	Specimen Number	Settlement Cracks	Crack Width	Crack Length, in.	Average Cracking Intensity
S273	7	2.75	74	1	Yes	< 2 mils	2	0.132
				2	Yes	< 2 mils	1.75	
				3	Yes	2 mils	1	
S274	8.25	5.25	74	1	Yes	< 2 mils	2.5	0.16
				2	Yes	< 2 mils	1.75	
				3	Yes	< 2 mils	1.5	
S275	10.5	8	73	1	Yes	< 2 mils	2.25	0.194
				2	Yes	< 2 mils	2	
				3	Yes	2 mils	2.75	
S276	8.75	4.5	73	1	Yes	< 2 mils	1	0.063
				2	Yes	< 2 mils	0.5	
				3	Yes	< 2 mils	0.75	
S277	9	6	73	1	Yes	2 mils	5.5	0.194
				2	Yes	< 2 mils	0.75	
				3	Yes	3 mils	0.75	
S278	8	3.25	73	1	Yes	< 2 mils	3	0.146
				2	Yes	< 2 mils	1	
				3	Yes	< 2 mils	1.25	
S279	8	3.5	75	1	Yes	< 2 mils	0.5	0.056
				2	Yes	< 2 mils	0.75	
				3	Yes	< 2 mils	0.75	
S280	8.5	3	73	1	Yes	< 2 mils	0.75	0.09
				2	Yes	< 2 mils	0.75	
				3	Yes	< 2 mils	1.75	
S281	9.5	4.5	72	1	Yes	2 mils	1.75	0.167
				2	Yes	2 mils	1.25	
				3	Yes	2 mils	3	
S282	10.75	7	72	1	Yes	2 mils	2.5	0.264
				2	Yes	2 mils	2	
				3	Yes	< 2 mils	5	
S283	9.5	5.5	73	1	Yes	< 2 mils	1.25	0.146
				2	Yes	< 2 mils	0.75	
				3	Yes	< 2 mils	3.25	

* Slump before the addition of the crack reduction technology.
** Slump after the addition of the crack reduction technology.

Table B.6: Settlement cracking results of F-3 fiber series.

Mixture No.	Initial Slump*, in.	Final Slump**, in.	Concrete Temperature, ° F	Specimen Number	Settlement Cracks	Crack Width	Crack Length, in.	Average Cracking Intensity
S217	4	2.75	75	1	Yes	2 mils	2	0.139
				2	Yes	< 2 mils	1.25	
				3	Yes	< 2 mils	1.75	
S218	6.25	4	74	1	Yes	< 2 mils	2	0.125
				2	Yes	< 2 mils	1.5	
				3	Yes	< 2 mils	1	
S219	4.25	2.5	75	1	Yes	< 2 mils	0.5	0.069
				2	Yes	< 2 mils	0.5	
				3	Yes	< 2 mils	1.5	
S220	8.5	6.75	74	1	Yes	2 mils	1.25	0.188
				2	Yes	< 2 mils	1.5	
				3	Yes	2 mils	4	
S221	9	7.5	73	1	Yes	< 2 mils	5.25	0.229
				2	Yes	< 2 mils	1.5	
				3	Yes	2 mils	1.5	
S222	8	5.75	75	1	Yes	< 2 mils	3.25	0.201
				2	Yes	< 2 mils	1.5	
				3	Yes	< 2 mils	2.5	
S223	5.5	3.5	74	1	Yes	< 2 mils	2	0.146
				2	Yes	< 2 mils	1	
				3	Yes	2 mils	2.25	
S224	7	4.5	75	1	Yes	< 2 mils	4.25	0.326
				2	Yes	< 2 mils	4.25	
				3	Yes	2 mils	3.25	
S227	9.25	7.25	75	1	Yes	2 mils	1.5	0.097
				2	Yes	2 mils	1.25	
				3	Yes	< 2 mils	0.75	
S228	6.5	3.25	75	1	Yes	< 2 mils	1	0.104
				2	Yes	< 2 mils	0.75	
				3	Yes	2 mils	2	
S228	6.5	3.25	75	1	Yes	< 2 mils	1	0.104
				2	Yes	< 2 mils	0.75	
				3	Yes	2 mils	2	
S229	9.5	8.5	74	1	Yes	3 mils	5.75	0.313
				2	Yes	2 mils	3.25	
				3	Yes	2 mils	2.25	

* Slump before the addition of the crack reduction technology.
** Slump after the addition of the crack reduction technology.

Table B.6 (Continued): Settlement cracking results of F-3 fiber series.

Mixture No.	Initial Slump*, in.	Final Slump**, in.	Concrete Temperature, ° F	Specimen Number	Settlement Cracks	Crack Width	Crack Length, in.	Average Cracking Intensity
S230	9.25	8.25	74	1	Yes	< 2 mils	6.25	0.326
				2	Yes	< 2 mils	2.25	
				3	Yes	2 mils	3.25	

* Slump before the addition of the crack reduction technology.
** Slump after the addition of the crack reduction technology.

Table B.7: Settlement cracking results of 1.5 lb/yd^3 of F-4 fiber series.

Batch No.	Initial Slump*, in.	Final Slump**, in.	Concrete Temperature, ° F	Specimen Number	Settlement Cracks	Crack Width	Crack Length, in.	Average Cracking Intensity
S242	8	6.25	74	1	Yes	< 2 mils	2.25	0.139
				2	Yes	< 2 mils	1.5	
				3	Yes	< 2 mils	1.25	
S243	6.25	4.5	74	1	Yes	< 2 mils	2	0.181
				2	Yes	2 mils	1.75	
				3	Yes	2 mils	2.75	
S244	4	2.75	74	1	Yes	< 2 mils	0.75	0.076
				2	Yes	< 2 mils	0.5	
				3	Yes	< 2 mils	1.5	
S245	8	7	74	1	Yes	< 2 mils	1.75	0.132
				2	Yes	< 2 mils	1.75	
				3	Yes	< 2 mils	1.25	
S246	8.25	6	72	1	Yes	< 2 mils	2.5	0.174
				2	Yes	< 2 mils	2	
				3	Yes	< 2 mils	1.75	
S248	9.5	8.25	73	1	Yes	< 2 mils	2.5	0.278
				2	Yes	< 2 mils	4.25	
				3	Yes	< 2 mils	3.25	
S250	8.5	7.5	73	1	Yes	< 2 mils	0.5	0.188
				2	Yes	< 2 mils	2	
				3	Yes	< 2 mils	4.25	
S251	6.75	4.25	72	1	Yes	2 mils	1.25	0.188
				2	Yes	2 mils	3.25	
				3	Yes	2 mils	2.25	
S252	5.25	2.75	73	1	Yes	< 2 mils	3	0.201
				2	Yes	< 2 mils	2.25	
				3	Yes	< 2 mils	2	
S253	6.25	4.5	73	1	Yes	< 2 mils	2.25	0.222
				2	Yes	< 2 mils	2.25	
				3	Yes	< 2 mils	3.5	
S254	6.75	5	73	1	Yes	< 2 mils	2.5	0.167
				2	Yes	< 2 mils	1.75	
				3	Yes	< 2 mils	1.75	

* Slump before the addition of the crack reduction technology.
** Slump after the addition of the crack reduction technology.

Table B.7 (Continued): Settlement cracking results of 1.5 lb/yd^3 of F-4 fiber series.

Batch No.	Initial Slump*, in.	Final Slump**, in.	Concrete Temperature, ° F	Specimen Number	Settlement Cracks	Crack Width	Crack Length, in.	Average Cracking Intensity
S255	4	3	74	1	Yes	< 2 mils	1.75	0.111
				2	Yes	< 2 mils	1	
				3	Yes	< 2 mils	1.25	

* Slump before the addition of the crack reduction technology.
** Slump after the addition of the crack reduction technology.

Table B.8: Settlement cracking results of 3 lb/yd^3 of F-4 fiber series.

Batch No.	Initial Slump*, in.	Final Slump**, in.	Concrete Temperature, ° F	Specimen Number	Settlement Cracks	Crack Width	Crack Length, in.	Crack Length/Bar Length
S231	6.25	3.75	74	1	Yes	< 2 mils	0.75	0.063
				2	Yes	< 2 mils	1.25	
				3	Yes	< 2 mils	0.25	
S232	5.25	3.5	74	1	Yes	< 2 mils	1.25	0.132
				2	Yes	< 2 mils	1.5	
				3	Yes	< 2 mils	2	
S233	4.5	2.5	75	1	Yes	< 2 mils	1.25	0.104
				2	Yes	< 2 mils	1	
				3	Yes	< 2 mils	1.5	
S234	8.25	5.5	74	1	Yes	< 2 mils	2.75	0.208
				2	Yes	< 2 mils	1.75	
				3	Yes	< 2 mils	3	
S235	9.25	7	73	1	Yes	< 2 mils	2.75	0.174
				2	Yes	< 2 mils	1	
				3	Yes	< 2 mils	2.5	
S236	8.25	6.5	74	1	Yes	< 2 mils	1.25	0.104
				2	Yes	< 2 mils	0.25	
				3	Yes	< 2 mils	2.25	
S237	7	4.75	74	1	Yes	< 2 mils	1.5	0.125
				2	Yes	< 2 mils	0.5	
				3	Yes	< 2 mils	2.5	
S238	10	8.5	73	1	Yes	2 mils	4	0.278
				2	Yes	2 mils	4.25	
				3	Yes	2 mils	1.75	
S239	9.5	8	73	1	Yes	2 mils	3.75	0.278
				2	Yes	< 2 mils	2.75	
				3	Yes	2 mils	3.5	
S240	4	2.75	75	1	Yes	< 2 mils	1	0.167
				2	Yes	< 2 mils	1.25	
				3	Yes	< 2 mils	3.75	
S241	5	3	75	1	Yes	2 mils	2.5	0.229
				2	Yes	< 2 mils	1.5	
				3	Yes	< 2 mils	4.25	

* Slump before the addition of the crack reduction technology.
** Slump after the addition of the crack reduction technology.

Table B.9: Settlement cracking results of VMA-1 series.

Mixture No.	Initial Slump*, in.	Final Slump**, in.	Concrete Temperature, ° F	Specimen Number	Settlement Cracks	Crack Width	Crack Length, in.	Crack Length/Bar Length
S180	4.75	2.75	74	1	Yes	< 2 mils	2.75	0.215
				2	Yes	< 2 mils	1.5	
				3	Yes	< 2 mils	3.5	
S181	7.5	4.25	75	1	Yes	< 2 mils	6.5	0.472
				2	Yes	< 2 mils	5	
				3	Yes	< 2 mils	5.5	
S182	3.25	1.75	74	1	Yes	< 2 mils	2.75	0.215
				2	Yes	< 2 mils	0.75	
				3	Yes	< 2 mils	4.25	
S183	7.25	5.5	72	1	Yes	< 2 mils	5.75	0.347
				2	Yes	< 2 mils	2.25	
				3	Yes	< 2 mils	4.5	
S188	8	5	74	1	Yes	< 2 mils	4	0.41
				2	Yes	< 2 mils	5.75	
				3	Yes	< 2 mils	5	
S191	7.5	4.25	74	1	Yes	2 mils	8.5	0.549
				2	Yes	< 2 mils	6.5	
				3	Yes	< 2 mils	4.75	
S192	8.5	5.5	74	1	Yes	< 2 mils	7.75	0.59
				2	Yes	2 mils	8.75	
				3	Yes	2 mils	4.75	
S202	7.5	4.75	74	1	Yes	2 mils	1.5	0.271
				2	Yes	< 2 mils	4.5	
				3	Yes	2 mils	3.75	
S203	9.5	7.75	74	1	Yes	2 mils	10.25	0.563
				2	Yes	< 2 mils	2.5	
				3	Yes	< 2 mils	7.5	
S205	8.5	7.5	75	1	Yes	2 mils	6.75	0.493
				2	Yes	< 2 mils	3.75	
				3	Yes	< 2 mils	7.25	

* Slump before the addition of the crack reduction technology.
** Slump after the addition of the crack reduction technology.

Table B.9 (Continued): Settlement cracking results of VMA-1 series.

Mixture No.	Initial Slump*, in.	Final Slump**, in.	Concrete Temperature, ° F	Specimen Number	Settlement Cracks	Crack Width	Crack Length, in.	Crack Length/Bar Length
S209	8	5	74	1	Yes	< 2 mils	3.5	0.326
				2	Yes	< 2 mils	2.25	
				3	Yes	< 2 mils	6	
S210	8.5	6	74	1	Yes	< 2 mils	1	0.396
				2	Yes	< 2 mils	5	
				3	Yes	< 2 mils	8.25	
S211	8.5	6.25	74	1	Yes	2 mils	4.25	0.306
				2	Yes	< 2 mils	1.25	
				3	Yes	< 2 mils	5.5	
S212	9	7.25	74	1	Yes	2 mils	5	0.639
				2	Yes	2 mils	8.75	
				3	Yes	2 mils	9.25	
S213	7.25	4.25	73	1	Yes	< 2 mils	6.5	0.306
				2	Yes	< 2 mils	3	
				3	Yes	< 2 mils	1.5	
S214	4.5	2.5	72	1	Yes	2 mils	3.75	0.313
				2	Yes	< 2 mils	3.75	
				3	Yes	< 2 mils	3.75	
S216	8.5	5.25	75	1	Yes	3 mils	6	0.333
				2	Yes	< 2 mils	2.25	
				3	Yes	2 mils	3.75	

* Slump before the addition of the crack reduction technology.
** Slump after the addition of the crack reduction technology.

APPENDIX C

STUDENT'S T-TEST RESULTS

Table C.1: Student's t-test results for Control-2 and Control-1 series.

Slump (in.)	Average Control-2 Mean	Average Control-1 Mean	Control-2 SD*	Control-1 SD	n** Control-2	n Control-1	α***	t	Difference
1	0.459	0.225	0.117	0.161	18	26	6.85E-06	5.15	Statistically Significant
2	0.495	0.281					2.83E-05	4.71	Statistically Significant
3	0.531	0.338					0.000114	4.27	Statistically Significant
4	0.568	0.394					0.000438	3.82	Statistically Significant
5	0.604	0.450					0.00159	3.38	Statistically Significant
6	0.640	0.507					0.00539	2.94	Statistically Significant
7	0.677	0.563					0.0167	2.50	Statistically Significant
8	0.713	0.620					0.0465	2.05	Statistically Significant

* Standard Deviation

** Number of samples

*** Level of significance, which represents the probability that any apparent differences in the data sets are due to random variation and not statistically meaningful differences

Table C.2: Student's t-test results for Control-2 and Control-3 series.

Slump (in.)	Average Control-3 Mean	Average Control-2 Mean	Control-3 SD	Control-2 SD	n Control-3	n Control-2	α	T	Difference
1	0.286	0.459	0.0848	0.117	14	18	6.41E-05	4.64	Statistically Significant
2	0.367	0.495					0.00178	3.436	Statistically Significant
3	0.449	0.531					0.0342	2.22	Statistically Significant
4	0.530	0.568					0.322	1.01	Not Statistically Significant
5	0.612	0.604					0.840	0.204	Not Statistically Significant
6	0.693	0.640					0.167	1.42	Not Statistically Significant
7	0.774	0.677					0.0135	2.63	Statistically Significant
8	0.856	0.713					0.000595	3.84	Statistically Significant

Table C.3: Student's t-test results for Control-3 and VMA-1 series.

Slump (in.)	Average Control-3 Mean	Average VMA-1 Mean	Control-3 SD	VMA-1 SD	n Control-3	n VMA-1	α	T	Difference
1	0.286	0.192	0.0848	0.0957	14	17	0.00756	2.87	Statistically Significant
2	0.367	0.243					0.000686	3.80	Statistically Significant
3	0.449	0.293					5.39E-05	4.73	Statistically Significant
4	0.530	0.344					4.09E-06	5.66	Statistically Significant
5	0.612	0.395					3.23E-07	6.59	Statistically Significant
6	0.693	0.446					2.77E-08	7.51	Statistically Significant
7	0.774	0.497					2.64E-09	8.44	Statistically Significant
8	0.856	0.548					2.81E-10	9.37	Statistically Significant

Table C.4: Student's t-test results for Control-3 and F-1 fiber series.

Slump (in.)	Average Control-3 Mean	Average F-1 Mean	Control-3 SD	F-1 SD	n Control-3	n F-1	α	T	Difference
1	0.286	0.105	0.0848	0.0444	14	11	1.57E-06	6.40	Statistically Significant
2	0.367	0.129					1.67E-08	8.45	Statistically Significant
3	0.449	0.152					3.07E-10	10.5	Statistically Significant
4	0.530	0.176					9.19E-12	12.5	Statistically Significant
5	0.612	0.199					4.13E-13	14.6	Statistically Significant
6	0.693	0.223					2.60E-14	16.6	Statistically Significant
7	0.774	0.247					2.15E-15	18.7	Statistically Significant
8	0.856	0.270					2.24E-16	20.7	Statistically Significant

Table C.5: Student's t-test results for Control-3 and F-2 fiber series.

Slump (in.)	Average Control-3 Mean	Average F-2 Mean	Control-3 SD	F-2 SD	n Control-3	n F-2	α	T	Difference
1	0.286	0.0476	0.0848	0.0409	14	11	1.37E-08	8.54	Statistically Significant
2	0.367	0.0733	0.0848	0.0409	14	11	2.81E-10	10.5	Statistically Significant
3	0.449	0.0990	0.0848	0.0409	14	11	9.20E-12	12.5	Statistically Significant
4	0.530	0.125	0.0848	0.0409	14	11	4.43E-13	14.5	Statistically Significant
5	0.612	0.150	0.0848	0.0409	14	11	2.94E-14	16.5	Statistically Significant
6	0.693	0.176	0.0848	0.0409	14	11	2.55E-15	18.5	Statistically Significant
7	0.774	0.202	0.0848	0.0409	14	11	2.75E-16	20.5	Statistically Significant
8	0.856	0.228	0.0848	0.0409	14	11	3.59E-17	22.5	Statistically Significant

Table C.6: Student's t-test results for Control-3 and F-3 fiber eries.

Slump (in.)	Average Control-3 Mean	Average F-3 Mean	Control-3 SD	F-3 SD	n Control-3	n F-3	α	T	Difference
1	0.286	0.075	0.0848	0.0556	14	12	1.36E-07	7.35	Statistically Significant
2	0.367	0.101	0.0848	0.0556	14	12	2.05E-09	9.29	Statistically Significant
3	0.449	0.127	0.0848	0.0556	14	12	4.98E-11	11.2	Statistically Significant
4	0.530	0.153	0.0848	0.0556	14	12	1.84E-12	13.2	Statistically Significant
5	0.612	0.179	0.0848	0.0556	14	12	9.63E-14	15.1	Statistically Significant
6	0.693	0.205	0.0848	0.0556	14	12	6.77E-15	17.0	Statistically Significant
7	0.774	0.231	0.0848	0.0556	14	12	6.08E-16	18.9	Statistically Significant
8	0.856	0.257	0.0848	0.0556	14	12	6.72E-17	20.9	Statistically Significant

Table C.7: Student's t-test results for Control-3 and 1.5 lb/yd^3 F-4 fiber series.

Slump (in.)	Average Control-3 Mean	Average F-4 Mean	Control-3 SD	F-4 SD	n Control-3	n F-4	α	T	Difference
1	0.286	0.118	0.0848	0.0463	14	12	2.57E-06	6.11	Statistically Significant
2	0.367	0.131					8.43E-09	8.61	Statistically Significant
3	0.449	0.144					6.15E-11	11.1	Statistically Significant
4	0.530	0.157					9.06E-13	13.6	Statistically Significant
5	0.612	0.170					2.34E-14	16.1	Statistically Significant
6	0.693	0.1824					9.45E-16	18.6	Statistically Significant
7	0.774	0.195					5.45E-17	21.1	Statistically Significant
8	0.856	0.208					4.19E-18	23.6	Statistically Significant

Table C.8: Student's t-test results for Control-3 and 3.0 lb/yd^3 F-4 fiber series.

Slump (in.)	Average Control-3 Mean	Average F-4 Mean	Control-3 SD	F-4 SD	n Control-3	n F-4	α	T	Difference
1	0.286	0.0920	0.0848	0.0575	14	11	1.31E-06	6.48	Statistically Significant
2	0.367	0.111					1.30E-08	8.57	Statistically Significant
3	0.449	0.130					2.26E-10	10.7	Statistically Significant
4	0.530	0.149					6.53E-12	12.8	Statistically Significant
5	0.612	0.168					2.86E-13	14.8	Statistically Significant
6	0.693	0.187					1.76E-14	16.9	Statistically Significant
7	0.774	0.206					1.43E-15	19.0	Statistically Significant
8	0.856	0.225					1.47E-16	21.1	Statistically Significant

Table C.9: Student's t-test results for F-1 fiber and F-2 fiber series.

Slump (in.)	Average F-2 Mean	Average F-1 Mean	F-2 SD	F-1 SD	n F-2	n F-1	α	t	Difference
1	0.0476	0.105	0.0409	0.0444	11	11	0.00500	3.15	Statistically Significant
2	0.0733	0.129					0.00650	3.04	Statistically Significant
3	0.0990	0.152					0.00842	2.92	Statistically Significant
4	0.125	0.176					0.0109	2.81	Statistically Significant
5	0.150	0.199					0.0140	2.69	Statistically Significant
6	0.176	0.223					0.0180	2.58	Statistically Significant
7	0.202	0.247					0.0231	2.46	Statistically Significant
8	0.228	0.270					0.0294	2.35	Statistically Significant

Table C.10: Student's t-test results for F-1 fiber and F-3 fiber series.

Slump (in.)	Average F-3 Mean	Average F-1 Mean	F-3 SD	F-1 SD	n F-3	n F-1	α	t	Difference
1	0.075	0.105	0.0556	0.0444	12	11	0.170	1.42	Not Statistically Significant
2	0.101	0.129					0.205	1.31	Not Statistically Significant
3	0.127	0.152					0.246	1.19	Not Statistically Significant
4	0.153	0.176					0.292	1.08	Not Statistically Significant
5	0.179	0.199					0.345	0.970	Not Statistically Significant
6	0.205	0.223					0.403	0.850	Not Statistically Significant
7	0.231	0.247					0.468	0.740	Not Statistically Significant
8	0.257	0.270					0.538	0.630	Not Statistically Significant

Table C.11: Student's t-test results for F-1 fiber and 1.5 lb/yd³ F-4 fiber series.

Slump (in.)	Average 1.5 lb/yd³ F-4 Mean	Average F-1 Mean	F-4 SD	F-1 SD	n F-4	n F-1	α	t	Difference
1	0.118	0.105	0.0463	0.0444	12	11	0.503	0.680	Not Statistically Significant
2	0.131	0.129					0.909	0.120	Not Statistically Significant
3	0.144	0.152					0.658	0.450	Not Statistically Significant
4	0.157	0.176					0.322	1.01	Not Statistically Significant
5	0.170	0.199					0.129	1.58	Not Statistically Significant
6	0.182	0.223					0.0440	2.14	Statistically Significant
7	0.195	0.247					0.0132	2.71	Statistically Significant
8	0.208	0.270					0.00364	3.27	Statistically Significant

Table C.12: Student's t-test results for F-1 fiber and 3.0 lb/yd³ F-4 fiber series.

Slump (in.)	Average 3 lb/yd³ F-4 Mean	Average F-1 Mean	F-4 SD	F-1 SD	n F-4	n F-1	α	t	Difference
1	0.0920	0.105	0.0575	0.0444	11	11	0.571	0.580	Not Statistically Significant
2	0.111	0.129					0.439	0.790	Not Statistically Significant
3	0.130	0.152					0.327	1.01	Not Statistically Significant
4	0.149	0.176					0.237	1.22	Not Statistically Significant
5	0.168	0.199					0.167	1.43	Not Statistically Significant
6	0.187	0.223					0.115	1.65	Not Statistically Significant
7	0.206	0.247					0.0771	1.86	Not Statistically Significant
8	0.225	0.270					0.0507	2.08	Not Statistically Significant

Table C.13: Student's t-test results for F-2 fiber and F-3 fiber series.

Slump (in.)	Average F-3 Mean	Average F-2 Mean	F-3 SD	F-2 SD	n F-3	n F-2	α	t	Difference
1	0.075	0.0476	0.0556	0.0409	12	11	0.196	1.33	Not Statistically Significant
2	0.101	0.0733					0.192	1.35	Not Statistically Significant
3	0.127	0.0990					0.187	1.36	Not Statistically Significant
4	0.153	0.125					0.182	1.38	Not Statistically Significant
5	0.179	0.150					0.178	1.39	Not Statistically Significant
6	0.205	0.176					0.174	1.41	Not Statistically Significant
7	0.231	0.202					0.170	1.42	Not Statistically Significant
8	0.257	0.228					0.165	1.44	Not Statistically Significant

Table C.14: Student's t-test results for F-2 fiber and 1.5 lb/yd^3 F-4 fiber series.

Slump (in.)	Average 1.5 lb/yd^3 F-4 Mean	Average F-2 Mean	F-4 SD	F-2 SD	n F-4	n F-2	α	t	Difference
1	0.118	0.0476	0.0463	0.0409	12	11	0.000947	3.84	Statistically Significant
2	0.131	0.0733					0.00491	3.14	Statistically Significant
3	0.144	0.0990					0.0235	2.44	Statistically Significant
4	0.157	0.125					0.0959	1.74	Not Statistically Significant
5	0.170	0.150					0.308	1.04	Not Statistically Significant
6	0.182	0.176					0.734	0.340	Not Statistically Significant
7	0.195	0.202					0.726	0.360	Not Statistically Significant
8	0.208	0.228					0.303	1.05	Not Statistically Significant

Table C.15: Student's t-test results for F-2 fiber and 3.0 lb/yd^3 F-4 fiber series.

Slump (in.)	Average 3 lb/yd^3 F-4 Mean	Average F-2 Mean	F-4 SD	F-2 SD	n F-4	n F-2	α	t	Difference
1	0.0920	0.0476	0.0575	0.0409	11	11	0.0481	2.11	Statistically Significant
2	0.111	0.0733					0.0893	1.79	Not Statistically Significant
3	0.130	0.0990					0.158	1.47	Not Statistically Significant
4	0.149	0.125					0.265	1.15	Not Statistically Significant
5	0.168	0.150					0.418	0.830	Not Statistically Significant
6	0.187	0.176					0.617	0.510	Not Statistically Significant
7	0.206	0.202					0.853	0.190	Not Statistically Significant
8	0.225	0.228					0.897	0.130	Not Statistically Significant

Table C.16: Student's t-test results for F-3 fiber and 1.5 lb/yd^3 F-4 fiber series.

Slump (in.)	Average 1.5 lb/yd^3 F-4 Mean	Average F-3 Mean	F-4 SD	F-3 SD	n F-4	n F-3	α	t	Difference
1	0.118	0.075	0.0463	0.0556	12	12	0.0526	2.05	Statistically Significant
2	0.131	0.101					0.169	1.42	Not Statistically Significant
3	0.144	0.127					0.435	0.795	Not Statistically Significant
4	0.157	0.153					0.868	0.168	Not Statistically Significant
5	0.170	0.179					0.650	0.460	Not Statistically Significant
6	0.182	0.205					0.289	1.09	Not Statistically Significant
7	0.195	0.231					0.101	1.71	Not Statistically Significant
8	0.208	0.257					0.0287	2.34	Statistically Significant

Table C.17: Student's t-test results for F-3 fiber and 3.0 lb/yd^3 F-4 fiber series.

Slump (in.)	Average 3 lb/yd^3 F-4 Mean	Average F-3 Mean	F-4 SD	F-3 SD	n F-4	n F-3	α	t	Difference
1	0.0920	0.075	0.0575	0.0556	11	12	0.469	0.738	Not Statistically Significant
2	0.111	0.101					0.667	0.437	Not Statistically Significant
3	0.130	0.127					0.893	0.136	Not Statistically Significant
4	0.149	0.153					0.870	0.165	Not Statistically Significant
5	0.168	0.179					0.646	0.466	Not Statistically Significant
6	0.187	0.205					0.451	0.768	Not Statistically Significant
7	0.206	0.231					0.297	1.07	Not Statistically Significant
8	0.225	0.257					0.185	1.37	Not Statistically Significant

Table C.18: Student's t-test results for 1.5 lb/yd^3 and 3.0 lb/yd^3 F-4 fiber series.

Slump (in.)	Average 1.5 lb/yd^3 F-4 Mean	Average 3 lb/yd^3 F-4 Mean	1.5 lb/yd^3 F-4 SD	3 lb/yd^3 F-4 SD	n 1.5 lb/yd^3 F-4	n 3 lb/yd^3 F-4	α	t	Difference
1	0.118	0.0920	0.0463	0.0575	12	11	0.252	1.18	Not Statistically Significant
2	0.131	0.111					0.378	0.900	Not Statistically Significant
3	0.144	0.130					0.540	0.620	Not Statistically Significant
4	0.157	0.149					0.733	0.350	Not Statistically Significant
5	0.170	0.168					0.945	0.0700	Not Statistically Significant
6	0.182	0.187					0.838	0.210	Not Statistically Significant
7	0.195	0.206					0.633	0.480	Not Statistically Significant
8	0.208	0.225					0.455	0.760	Not Statistically Significant

APPENDIX D

SLUMP BEFORE AND AFTER THE ADDITION OF THE CRACK REDUCING ADDITIONS (INITIAL AND FINAL SLUMP)

The influence of adding crack reduction technologies on concrete slump is illustrated in this Appendix. Slump was measured in accordance with ASTM C143 before and after the addition of fibers or VMA. Figures D.1 through D.6 show the initial and final values of slump for the individual batches of concrete in each series. Results are plotted in order of increasing slump prior to the addition of the fibers or VMA. The mixture numbers are not related to batch numbers listed in Appendix B. As a general observation, the addition of fibers caused a greater reduction in slump for batches with lower initial slumps, while VMA-1 caused a reduction in slump that was independent of the initial slump.

Figure D.1 shows the slump values before and after the addition of F-1 fiber to the concrete. The average reduction in the slump after the addition of F-1 fiber in 11 mixtures was 2.25 in. (65 mm). The trend in Figure D.1 suggests a somewhat greater reduction in slump for batches with lower initial slumps.

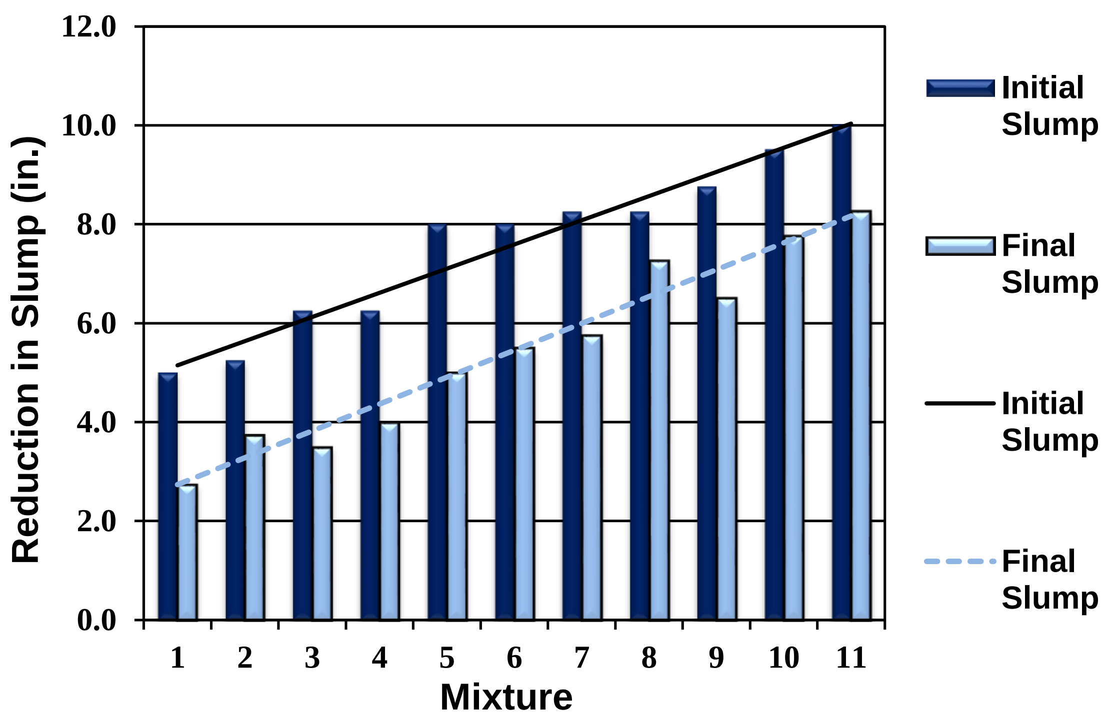

Figure D.1: Reduction in slump due to the addition of F-1 fiber to the concrete.

Figure D.2 shows the slump values before and after the addition of F-2 fiber to the concrete. The average reduction in the slump after the addition of F-2 fiber in 11 mixtures was 4 in. (100 mm). Figure D.2 illustrates a greater decrease in the slump for low initial slump mixtures compared to higher initial slump mixtures. This observation may be related to the higher bond that might develop between concrete and fibers in lower slump mixtures.

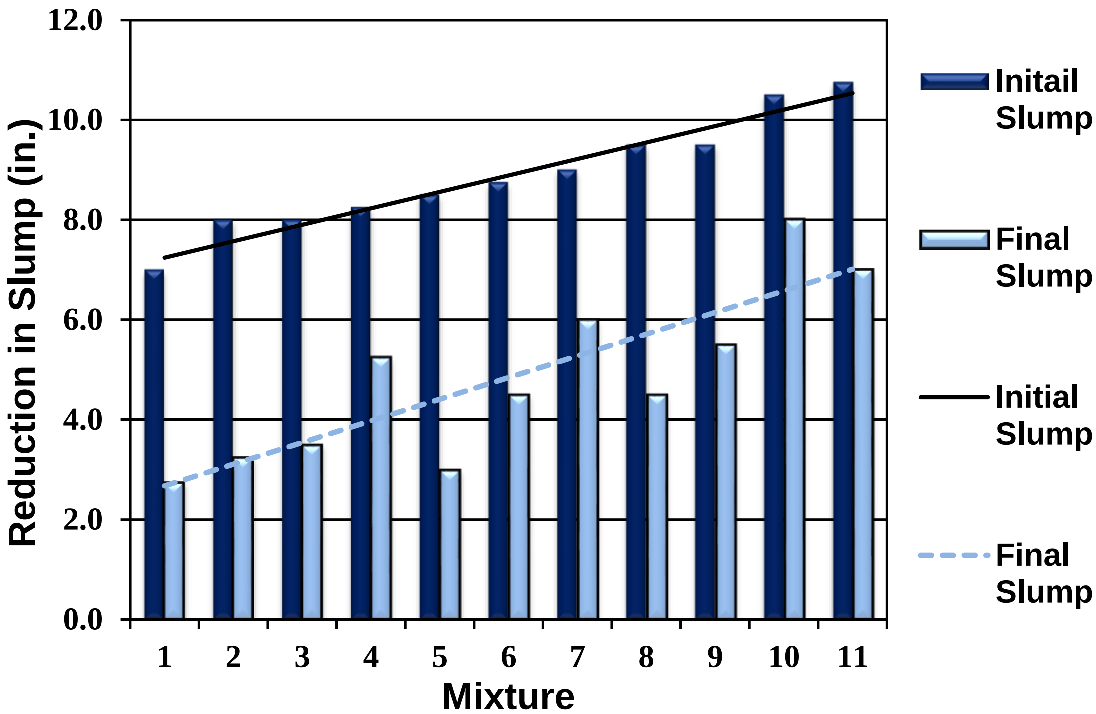

Figure D.2: Reduction in slump due to the addition of F-2 fiber to the concrete.

Figure D.3 shows the slump values before and after the addition of F-3 fiber to the concrete. The average reduction in the slump after the addition of F-3 fiber in 12 mixtures was 1.5 in. (45 mm). Mixtures with lower initial slump exhibited a slightly greater decrease in slump compared to mixtures with higher initial slumps.

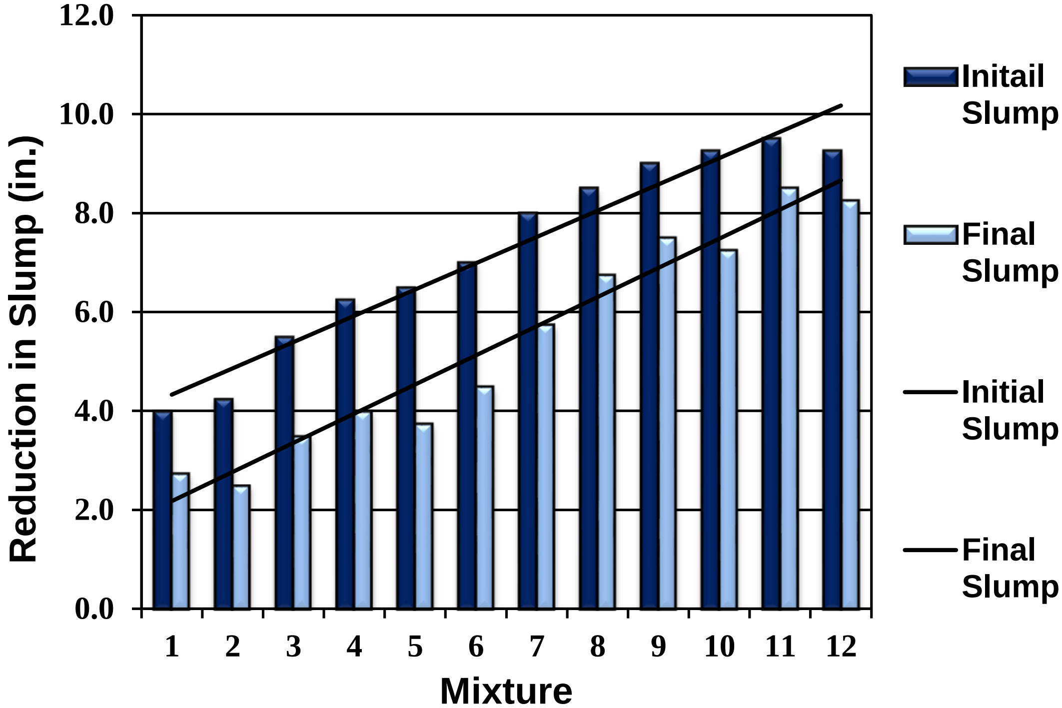

Figure D.3: Reduction in slump due to the addition of F-3 fiber to the concrete.

Figure D.4 shows the slump values before and after the addition of 1.5 lb/yd^3 (0.89 kg/m^3) of F-4 fiber to the concrete. The average reduction in the slump after the addition of F-4 fiber in 12 mixtures was 1.5 in. (40 mm). Mixtures with lower initial slump exhibited a slightly greater decrease in slump compared to mixtures with higher initial slumps.

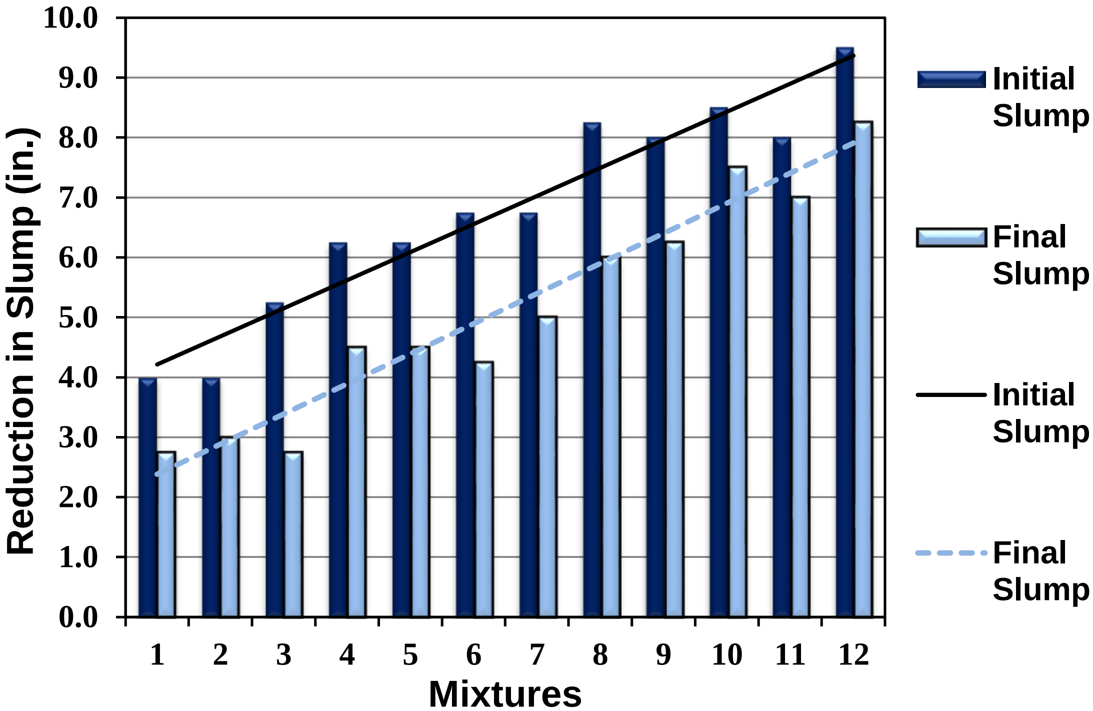

Figure D.4: Reduction in slump due to the addition of 1.5 lb/yd^3 (0.89 kg/m^3) of F-4 fiber to the concrete.

Figure D.5 shows the slump values before and after the addition of 3.0 lb/yd^3 (1.78 kg/m^3) of F-4 fiber to the concrete. The average reduction in the slump after the addition of F-4 fiber in 11 mixtures was 2 in. (50 mm). Doubling the dosage of F-4 fiber from 1.5 to 3.0 lb/yd^3 (0.89 to 1.78 kg/m^3) raised the average decrease in the slump by a magnitude of 0.5 in. (15 mm). Figure D.5 illustrates a nearly uniform decrease in the slump for all batches.

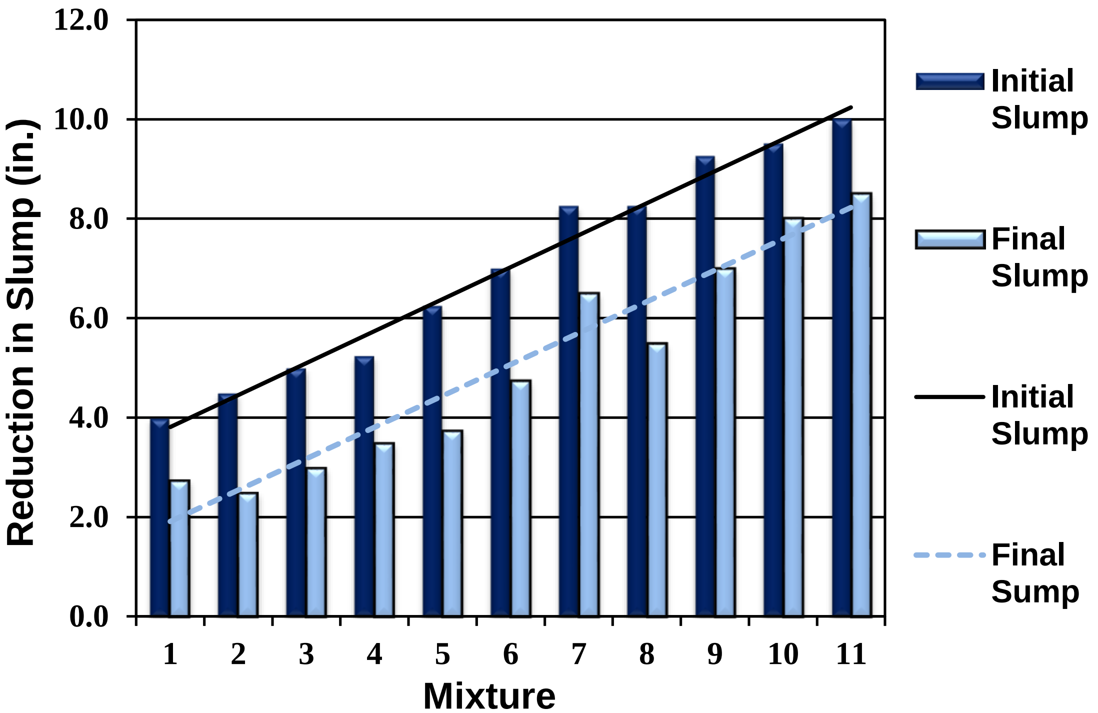

Figure D.5: Reduction in slump due to the addition of 3.0 lb/yd3 (1.78 kg/m^3) of F-4 fiber to the concrete.

Figure D.6 show the slump values before and after the addition of VMA-1 to the concrete. The average reduction in the slump after the addition of VMA-1 in 17 mixtures was 2.5 in. (65 mm). Figure D.6 illustrates that the decrease in the slump was nearly uniform across the range of slumps tested.

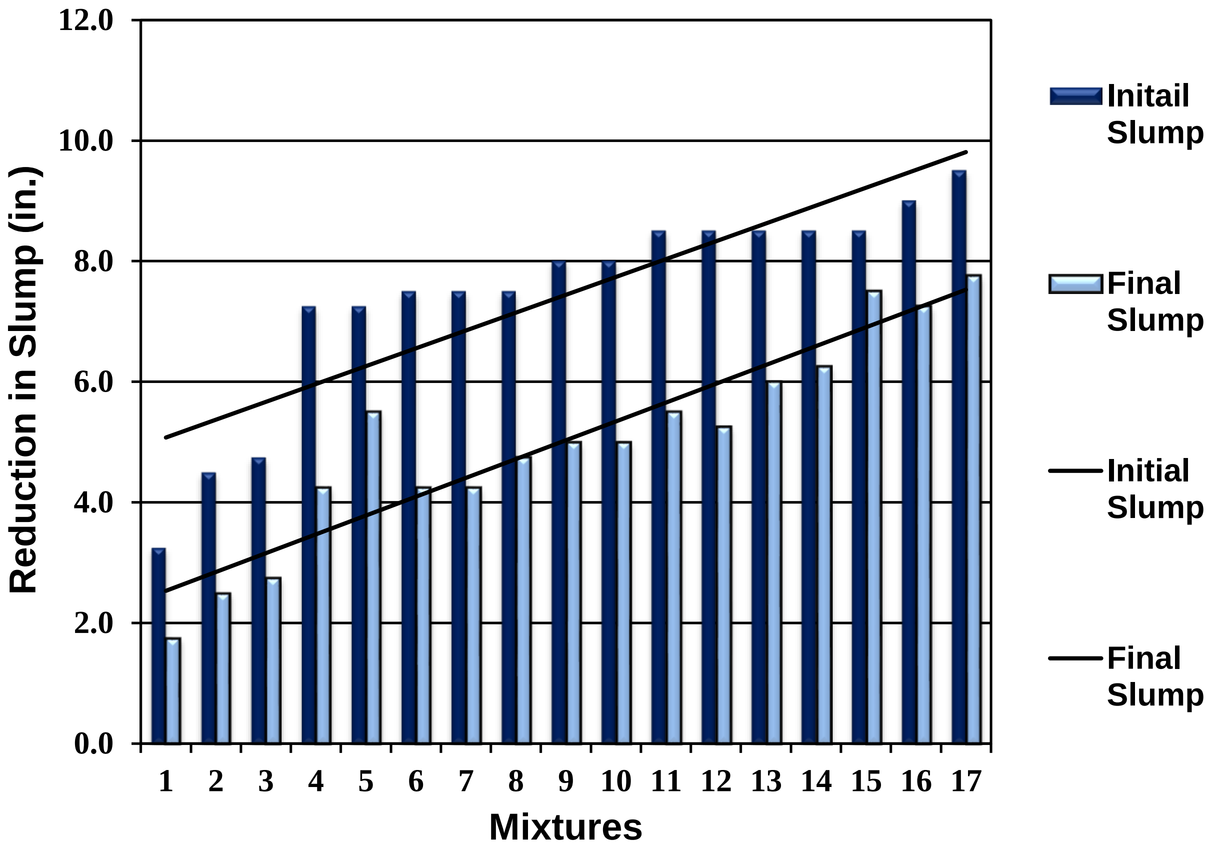

Figure D.6: Reduction in slump due to the addition of VMA-1 to the concrete.